THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# Facilitating the Implementation of Smart Maintenance

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# ABSTRACT

Innovations and rapid advancements in digital technologies in the manufacturing industry are setting high expectations of highly automated, intelligent and interconnected production systems. To bring these expectations to realisation and secure productive and sustainable production systems, maintenance organisations must develop accordingly. Thus, there is a need for organisational innovation in maintenance.

The way in which maintenance is organised in digitalised manufacturing is called "Smart Maintenance", and industrial companies need evidence-based guidance in pursuing such an implementation. Thus, the purpose of this thesis is to facilitate Smart Maintenance implementation. To this end, the thesis aims to support organisational innovation in maintenance, with organisations and all targeted employees becoming increasingly skilful, consistent and committed to working with Smart Maintenance. This aim was achieved through a mixed-methods approach comprising six studies.

Firstly, digitalisation in general and Smart Maintenance in particular, will require investment. This thesis reviews 24 maintenance models which can be used as support in calculating and describing the effects of maintenance. It also demonstrates an example of how to evaluate new technology (the impact of 5G technology on manufacturing performance). The thesis also identifies 11 factors influencing the investment process.

Secondly, to benefit from the technology, an organisation must develop accordingly. This means that development initiatives need to be managed. This thesis presents an overall consideration model for leading maintenance in digitalised manufacturing. In short, the role of a maintenance manager is changing from that of a technical manager into a leader of people and organisations in change. Further, the effects of Smart Maintenance can be followed up using maintenance performance indicators (PIs). This thesis analyses 170 PIs and structures them into 13 categories.

Thirdly, a strategic approach to Smart Maintenance helps in structuring such an implementation. This thesis proposes a strategy development process for Smart Maintenance implementation. The process is cyclical and continuously assesses the maintenance organisation to find new improvement areas. It thus continuously develops maintenance organisations and their way of working with Smart Maintenance.

All studies are related to the diffusion of innovations (DOI) theory, to structure the findings into a framework that supports organisational innovation in maintenance. This is a novel perspective in both research and practice. The framework provided in this thesis can be used as guidance by industry practitioners as they implement Smart Maintenance. Thus, industrial companies can continue their development towards digitalisation and move towards increasingly competitive and sustainable production systems.

**Keywords**: maintenance; manufacturing; innovation; digitalisation; Industry 4.0

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When I started as a Ph.D. student, I expected a challenging journey of continuous learning. I never thought this would be easy, and it wasn't. However, I could not have foreseen the intense mental and emotional rollercoaster I experienced during the process of becoming a Doctor of Philosophy; this added an extra dimension of challenges. However, looking back on this process, I am full of pride and gratitude. I've been surrounded by amazing people during this journey and would like to try and express my gratitude to you all here.

Firstly, I'd like to thank my supervisor, Professor Anders Skoogh. I am eternally grateful for your encouragement to accept this journey and for your support throughout. Your supervision has meant a lot to me and this thesis. Thank you, Anders!

I want to thank my examiner, Professor Johan Stahre and co-supervisor Professor Björn Johansson for thoughtful and useful advice along the way. Thanks also to Dr. Jon Bokrantz for the valuable discussions and contributions to the appended papers.

I have worked in an excellent internal environment alongside my colleagues at the Department. At division level, we have developed a great working environment in which we may challenge each other. Discussions and feedback may sound a bit "harsh" but what makes it possible is the friendly atmosphere and mutual respect within the Division; something of which we should be very proud! There are too many people to name but I'm honoured to have had the opportunity to work with you all.

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Above all, I wish to thank the person who, no matter what, makes me laugh every day. Dennis, I love you endlessly.

Camilla Lundgren
Gothenburg, 2021

# LIST OF APPENDED PAPERS

The six appended papers in this thesis are listed below, including the contributions of the authors.

**Paper I** **Quantifying the Effects of Maintenance – a Literature Review of Maintenance Models**

**Camilla Lundgren**, Anders Skoogh and Jon Bokrantz (2018)

Presented at the *51st CIRP Conference on Manufacturing Systems*, Stockholm, May 2018. Published in *Procedia CIRP,* vol. 72, pp. 1305-1310.

The study was planned by Camilla Lundgren and Anders Skoogh and the literature study conducted by Camilla. All authors participated in the workshop for categorising the literature. Camilla wrote the paper, with the support of Anders and Jon Bokrantz who provided valuable comments and advice.

**Paper II** **Factors Influencing Maintenance-related Investments in Industry: a Multiple-case Study**

**Camilla Lundgren**, Jon Bokrantz and Anders Skoogh (2021)

Published in *Journal of Quality in Maintenance Engineering,* vol. 27, no. 1, pp. 203-224.

The study was planned by Camilla Lundgren, with support from Jon Bokrantz and Anders Skoogh. Camilla collected the data and further analysed it, with support from Jon. Camilla wrote the paper, with supporting comments and advice from Jon and Anders.

**Paper III** **Performance Indicators for Measuring the Effects of Smart Maintenance**

**Camilla Lundgren**, Jon Bokrantz and Anders Skoogh (2021)

Published in *International Journal of Productivity and Performance Management,* vol. 70, no. 6, pp. 1291-1316.

Camilla Lundgren planned the study, with support from Jon Bokrantz and Anders Skoogh. Camilla conducted the literature study and the coding was done by Camilla and Jon. Camilla wrote the paper, with contributions from Jon and supporting comments and advice from Anders.

**Paper IV** **Determining the Impact of 5G technology on Manufacturing Performance Using a Modified TOPSIS Method**

**Camilla Lundgren**, Ebru Turanoglu Bekar, Maja Bärring, Johan Stahre, Anders Skoogh, Björn Johansson and Richard Hedman (2021)

Published in *International Journal of Computer Integrated Manufacturing,* published online (doi: 10.1080/0951192X.2021.1972465).

The study was initiated and planned by Camilla Lundgren and Johan Stahre. Camilla and Ebru Turanoglu Bekar planned the quantitative data analysis, and designed the data collection accordingly. Camilla collected all data and analysed the qualitative data and Ebru conducted the quantitative data analysis. Camilla, Ebru, and Maja Bärring contributed text to the manuscript, Johan, Anders Skoogh and Björn Johansson provided valuable comments and advice. Richard Hedman participated in the research project under which the study was conducted.

**Paper V** **A Strategy Development Process for Smart Maintenance Implementation**

**Camilla Lundgren**, Jon Bokrantz and Anders Skoogh (2021)

Published in *Journal of Manufacturing Technology Management,* vol. 32, no. 9, pp. 142-166.

The study was planned by Camilla Lundgren and Jon Bokrantz. Jon administered the questionnaire and Camilla conducted the workshops based on its results. Data collection from the workshop and the resulting work was done by Camilla. The data analysis was done by Camilla, with support from Jon and Anders. Camilla wrote the paper, with valuable advice from Jon and Anders.

**Paper VI** **How Industrial Maintenance Managers Perceive Socio-technical Changes in Leadership in the Context of Digitalized Manufacturing**

**Camilla Lundgren**, Cecilia Berlin, Anders Skoogh and Anders Källström (2021)

Manuscript submitted to a journal.

Cecilia Berlin, Anders Skoogh, and Anders Källström planned and conducted the interviews. Camilla Lundgren and Cecilia planned the data analysis (an initial scanning of the data from the interviews to agree on coding principles). The analysis and coding were done by Camilla, with support from Cecilia. Camilla and Cecilia wrote the paper, with valuable comments and advice from Anders and Anders.

# TABLE OF CONTENTS

# LIST OF ABBREVIATIONS

BSC – balanced scorecard

CBM – condition-based maintenance

CM – corrective maintenance

CMMS – computerised maintenance management system

DOI – diffusion of innovations

LCP - life-cycle profit

PHM – prognostics and health management

PM – preventive maintenance

RBM - risk-based maintenance

RCM – reliability-centred maintenance

STS – socio-technical systems

TPM – total productive maintenance

TQMain – total quality maintenance

VDM - value-driven maintenance

# 1 INTRODUCTION

Our society is currently undergoing substantial change. Today's innovations and technological development are extremely rapid, bringing easily accessible and reliable technology at low cost (Baur and Wee, 2015; Benzell and Brynjolfsson 2019). For many people, digital technologies are just a part of everyday life. People and things, such as phones, computers, watches and so on, are almost constantly connected. The number of interconnected devices is continuously increasing and projected to reach 28 billion by 2025 (Lueth, 2020).

The manufacturing industry is no exception in this technological shift. Digitalisation of the manufacturing industry, or "digitalised manufacturing", will transform production systems and lead to significant productivity improvements (Dalenogare et al., 2018; Monostori et al., 2016). Digitalised manufacturing is characterised by computer science and advanced manufacturing technology (Kagermann et al., 2013; Xu et al., 2018) including key technologies such as big data, cyber-physical systems (CPS), the Internet of things (IoT) and 3D-printing (Culot et al., 2020; Lu 2017; Monostori et al., 2016). There is a high level of automation, with production equipment and humans interconnected and continuously exchanging information. This makes it possible to decentralise decisions and control and thus have autonomously operating systems (Hermann et al., 2016; Monostori et al., 2016). It is clear that maintenance, described by Groover (2007) as "*procedures that make production systems work*", will be an important part of it all. At the same time, too many companies are experiencing too much equipment downtime. This is not associated with digitalised manufacturing. There is a need to develop maintenance organisations and their practices so that they meet the demands of digitalised manufacturing. We need organisational innovation in maintenance.

Maintenance in digitalised manufacturing is called "Smart Maintenance" (Bokrantz et al., 2020c), and industrial companies need evidence-based guidance in pursuing such an implementation. The research into maintenance technologies for digitalised manufacturing is under continuous development (see, for example, Compare et al., 2020; Li et al., 2017; Roy et al., 2016). However, Smart Maintenance is not limited to technical solutions. Despite this, research has so far devoted too little time to the organisational development needed to adapt maintenance organisations to working in digitalised environments (Silvestri et al., 2020). This thesis aims to change that, by providing support for organisational innovation in maintenance. This means the organisation and all targeted employees will become increasingly skilful, consistent and committed to working with Smart Maintenance, thus meet the demands of digitalised manufacturing.

## 1.1 VISION AND PURPOSE

My vision is to realise failure-free production systems and contribute to competitive and sustainable manufacturing industry via Smart Maintenance. Hence, the purpose of this thesis is to facilitate the implementation of Smart Maintenance in the manufacturing industry.

## 1.2 AIM AND RESEARCH QUESTIONS

I aim to provide support for organisational innovation in maintenance, with the organisation and all targeted employees becoming increasingly skilful, consistent and committed to working with Smart Maintenance.

Three sequential research questions were formulated in support of this aim:

### RQ1: How can Smart Maintenance investments be justified?

As there is a technological shift, investment is needed. However, not enough has been invested in maintenance and industry practitioners commonly perceive it as a challenge to get maintenance-related investment approved. Hence, RQ1 focuses on how Smart Maintenance investments can be justified.

### RQ2: How can Smart Maintenance initiatives be managed?

To benefit from the technology, an organisation and its individuals need to develop accordingly. Someone needs to be responsible for leading such change and its effects must be measured to ensure development in the anticipated direction. Thus, RQ2 focuses on how to manage Smart Maintenance initiatives. In other words, investment, activities and efforts which contribute to Smart Maintenance.

### RQ3: How can a strategic approach to Smart Maintenance implementation be developed?

Ideally, the implementation of Smart Maintenance might be packaged into a strategic approach to make it applicable. Hence, RQ3 focuses on the development of a strategic approach to Smart Maintenance implementation.

This thesis views Smart Maintenance from the perspective of organisational innovation. The three research questions and associated studies relate to the diffusion of innovations (DOI) theory in further describing and understanding how to facilitate the implementation of Smart Maintenance.

The definition of implementation in this thesis is based on "[...] *the transition period during which targeted organizational members ideally become increasingly skillful, consistent, and committed in their use of an innovation*" (Klein and Sorra, 1996, pp. 1057), which has been an inspiration in formulating its aims. This definition focuses on the transition period (time). However, this thesis also takes a process view of implementation. That is, it examines the transition period needed for concrete, targeted efforts and in which the organisation and all targeted employees become increasingly skilful, consistent and committed to working with Smart Maintenance.

## 1.3 DELIMITATIONS

This thesis focuses on the maintenance of production systems. A production system is regarded as an interplay of people, equipment and procedures, organised in a particular way that transforms tangible inputs (raw materials, semi-finished goods) and intangible inputs (knowledge, information) into outputs of goods or services (Bellgran and Säfsten, 2009; Groover, 2007).

This thesis assumes the theoretical domain of Smart Maintenance implementation to be broad, including all organisations with a maintenance function. Thus, empirical data was collected from a variety of organisations across multiple industrial sectors. Still, the thesis focuses primarily on the manufacturing industry as the main application area of Smart Maintenance. The majority of empirical data was collected from continuous and discrete part-manufacturing organisations.

Investments in technology (tangible assets) and human capital (intangible assets) are needed. However, this thesis only covers tangible investment. These usually follow a formal process and are thus easier to study, compared to intangible investment.

## 1.4 STRUCTURE OF THE THESIS

The thesis is structured as follows:

**Chapter 1, Introduction** presents the background of the thesis, followed by its vision, purpose, aim, research questions and delimitation.

**Chapter 2, Frame of Reference** provides a theoretical background to the DOI theory, digitalisation of the manufacturing industry, history of maintenance management, maintenance in digitalised manufacturing and maintenance strategy development. All are important in understanding the research presented in this thesis.

**Chapter 3, Research Approach** describes the research approach taken in this thesis, including epistemological assumptions, research designs and research methods.

**Chapter 4, Research Results** presents the results of the six studies (A-E) and their contribution to the research questions (RQ1, RQ2, RQ3).

**Chapter 5, Smart Maintenance Implementation – an Organisational Innovation** presents a theoretical interpretation of the results of the six studies (A-E). This chapter relates the results to the DOI theory and aims to describe how the organisation and all targeted employees can become increasingly skilful, consistent and committed to working with Smart Maintenance.

**Chapter 6, Discussion** discusses the research results and provides answers to the three research questions (RQ1, RQ2, RQ3). Further, academic and industrial contributions are presented, followed by a methodological discussion and reflections on limitations. The chapter ends by proposing future work.

**Chapter 7, Conclusions** summarises the major outcome of this thesis and presents its conclusions.

# 2 FRAME OF REFERENCE

*This chapter presents the frame of reference relevant to this thesis and the three research questions. The chapter starts with an introduction to the diffusion of innovations (DOI) theory, followed by a description of digitalisation of the manufacturing industry. An overview of the history of maintenance management is then given, followed by sections about maintenance in digitalised manufacturing and strategy development. The chapter ends with a summary of the research gap this thesis aims to fill. Table 1 provides an overview of how the research questions relate to the sections in this chapter.*

Table 1: Overview of the sections in this chapter and which RQs to which they relate.

| **Section in Frame of Reference** | **RQ1** | **RQ2** | **RQ3** |
|---|---|---|---|
| 2.1 Diffusion of innovations | x | x | x |
| 2.2 Digitalisation of the manufacturing industry | x | x | x |
| 2.3 Overview of the history of maintenance management | x | x | x |
| 2.4 Maintenance in digitalised manufacturing | x | x | x |
| 2.5 Maintenance strategy development | | | x |

## 2.1 DIFFUSION OF INNOVATIONS

*In this thesis, the DOI theory is used to further explain and understand the implementation of Smart Maintenance. Hence, this section is relevant to the whole thesis and thus all three research questions (RQ1, RQ2, RQ3).*

Innovation is a widely-used concept and its definition usually reflects the particular context in which innovation is described (Damanpour and Evan, 1984). It may be common to associate the word innovation with product innovation - a new or significantly improved good, or process innovation – a new or significantly improved production method. However, the concept of innovation also includes marketing and organisational aspects. OECD/European Communities (2018) has defined innovation as "*the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations*". Focusing on the latter, organisational innovation includes both new to state-of-the-art and new to the unit (the specific organisation) (Mol and Birkinshaw, 2009; Rogers, 2003). This means that, even though an organisational method may be well-established in some companies, there is an organisational innovation going on for the individual company implementing the organisational method that is new to them. Moreover, it is important to distinguish between innovation adoption and innovation implementation. While innovation adoption refers to the use of innovation, innovation implementation is *"[...] the transition period during which targeted organizational members ideally become increasingly skillful, consistent, and committed in their use of an innovation"* (Klein and Sorra, 1996, pp. 1057). The fundamental organisational challenge of innovation implementation is to change the behaviour of individuals within a system (Greenhalgh et al., 2004; Klein and Sorra, 1996).

Implementation policies and practices leading to successful innovation implementation vary from case to case (Klein and Sorra, 1996; Larsson, 2020). However, five characteristics of innovations are particularly important, according to the DOI theory (Rogers, 2003):

(1) Relative advantage. The degree to which the innovation provides a perceived advantage, such as financial gain, social prestige and/or satisfaction, thus leading to greater motivation for change.

(2) Compatibility. How well an innovation fits the existing values and norms of the individual or organisation. The better the fit, the greater likelihood of innovation adoption and implementation.

(3) Complexity. An innovation that is perceived as difficult to use or understand will be adopted to a lesser extent than one that is simple and easy to understand.

(4) Trialability. If it is possible to try the innovation in stages and learn by doing, the degree of uncertainty will decrease. The innovation is more likely to be adopted or implemented, compared to one that is indivisible.

(5) Observability. This reflects the degree of visibility of the innovation's results. If the results are easy for individuals to see, its adoption or implementation is more likely, compared to an innovation with less prominent results.

The DOI theory has been used in a variety of disciplines, for example, operations management (Waring and Alexander, 2015), education (Dooley, 1999) and politics (policy-making) (Makse and Volden, 2011). The theory is rarely used within the maintenance field. However, a recent study by Tortorella et al., (2021) used DOI to identify drivers and barriers for integrating Industry 4.0 technologies into TPM practices. Rogers (2003) refers primarily to technical innovations but much is also applicable to organisational innovations (but with some differences) (Steiber, 2012; Boer and During, 2001). The relative advantage of organisational innovation cannot usually be calculated using a traditional return on investments model, as organisational innovations tend to influence the daily work of those within the organisation (Steiber, 2012). Since a relative advantage becomes more difficult to determine in advance, organisational innovations rely on belief in their relative advantage.

The compatibility of innovation depends on the values of each individual plus those within the organisation. This is also known as "innovation-value fit" (Klein and Sorra, 1996) and becomes even more important in organisational innovations (Steiber, 2012). The stronger the innovation-value fit, the stronger the commitment to implementing the innovation among employees, which increases their willingness to change. However, an innovation also depends on the implementation climate and "permission" to change. The combination of implementation climate and innovation-values fit has different organisational outcomes in employee behaviour (Klein and Sorra 1996). If there is a good innovation-value fit, a strong implementation climate will create enthusiasm, while a weak implementation climate will create frustration and disappointment. By contrast, a strong implementation climate combined with a poor innovation-value fit will create resistance, while a weak implementation climate will make employees feel relieved.

Complexity in technical innovations is mostly related to the complexity of the product; requiring a problem-solving focus to ensure a suitable solution to a technical problem (Boer and During, 2001). By contrast, the complexity of organisational innovations is of a different nature; aggregation of individuals, with their own perception of work procedures and norms (Greenhalgh et al., 2004) and with difficulties in observing, interpreting and testing of the innovations (Steiber, 2012).

Organisational innovations depend on a high degree of trialability that allows stepwise implementation and thus reduces the risk of uncertainties (Boer and During, 2001). The opposite is radical innovation. This involves radical changes in technology, work procedures or the like, which are not beneficial to organisational innovations. By contrast, a stepwise approach allows a combination of existing techniques and work procedures involving new ideas (Tushman and Nadler, 1986; Read, 2000). In addition to having a beneficial learning focus (Klein and Knight, 2005; Laforet, 2011), a stepwise approach to organisational innovation may also lead to a decrease in perceived complexity. This makes transparency in progress a prerequisite (Boer and During, 2001). A mixture of top-down and bottom-up approaches is beneficial in avoiding uncertainties; top-down to set the direction and bottom-up so that employees can respond quickly to uncertainties (Boer and During, 2001).

A highly important yet commonly neglected aspect of organisational innovation is observability (Boer and During, 2001). Observability and internal diffusion (communication and visualisation of the progress and results of an innovation) remain in the background in favour of solving technical problems (Boer and During, 2001). As with the anticipated impact of an innovation, it may prove challenging to separate the results of an innovation from other variables likely to have an impact (Read, 2000). Nevertheless, for organisational innovation, internal diffusion remains critical in creating awareness of changes and maintaining employee motivation (Boer and During, 2001; Klein and Sorra, 1996).

## 2.2 DIGITALISATION OF THE MANUFACTURING INDUSTRY

*Digitalised manufacturing is the context in which Smart Maintenance will be implemented. Thus, this section relates to all the research questions (RQ1, RQ2 and RQ3).*

Innovations and advancements in technology have long affected our society. But the developments of recent years have accelerated our dependency on technology. We use smartphones to control our homes, we meet and socialise over the Internet and we are anticipating autonomous cars, to name some examples. The manufacturing industry has also noted the benefit of using technological innovations and aims to increase productivity and preserve or even increase its global competitiveness (Dalenogare et al., 2018; Hermann et al., 2016). In 2011, the German government originated the term "Industrie 4.0" as a strategic movement to work on digitalising the manufacturing industry (Culot et al., 2020; Kagermann et al., 2013). Since then, "Industrie 4.0" has evolved in terms of what it comprises, with various definitions and similar concepts describing the same phenomena (Culot et al., 2020; Nosalska et al., 2020; Büchi et al., 2020). Examples include "smart manufacturing", "digital transformation", "Fourth Industrial Revolution" and "smart factories" (Hermann et al., 2016; Kang et al., 2016a). For want of an exact definition, Industry 4.0 and similar concepts seem to have some important characteristics in common. They are based on advanced manufacturing technology and computer science (Kagermann *et al*., 2013; Xu et al., 2018) including links between the virtual and physical worlds (Büchi et al., 2020) and they have transparency of information and decentralisation of decisions (Hermann et al., 2016). This is enabled by key technologies such as big data, cyber-physical systems (CPS), the Internet of things (IoT), cloud computing and 3D printing (Culot et al., 2020; Lu, 2017). Not only will the digitalisation of industry and associated technologies change the production systems themselves, it will also change value chains and business models, whilst enabling personalised smart products (Nosalska et al., 2020). This thesis will henceforth use the term "digitalised manufacturing" to refer to the concept of digitalisation of the manufacturing industry.

Whilst digitalised manufacturing is expected to include autonomous systems, too many companies are experiencing excess equipment downtime, with overall equipment effectiveness (OEE) at around 50% (Ylipää et al., 2017). This indicates a huge potential for improvement, requiring several functions to work together to ensure production systems remain highly productive. The maintenance organisation is responsible for "*procedures that make production systems work*" (Groover, 2007) and will play a particularly important role in realising digitalised manufacturing.

## 2.3 OVERVIEW OF THE HISTORY OF MAINTENANCE MANAGEMENT

*This section presents the basic knowledge on the main topic of this thesis and makes this section relevant to all the research questions (RQ1, RQ2, RQ3).*

This thesis focuses on the maintenance of production systems. These are regarded as an interplay of people, equipment and procedures, organised in a particular order to transform tangible inputs (raw materials, semi-finished goods) and intangible inputs (knowledge, information) into outputs of goods or services (Bellgran and Säfsten, 2009; Groover, 2007). Maintenance is an important part of a production system, ensuring that it runs as expected. An established definition of maintenance is "*the combination of all technical, administrative and managerial actions, during the life-cycle of an item intended to retain it in, or restore it to, a state in which it can perform a required function*" (CEN, 2001; EN 13306, 2010). Thus, maintenance is about repairing equipment that breaks down but also about taking preventive action, to reduce the risk of non-functional equipment.

This is usually referred to as reactive/corrective maintenance or preventive maintenance (EN 13306, 2010).

Although the importance of maintenance has long been acknowledged in both theory and practice (Dekker, 1996; Moubray, 1997; Coetzee, 1999; Garg and Deshmukh, 2006; Fraser et al., 2015; Monostori et al., 2016), past developments in maintenance management have not kept pace with the development of production systems (Sherwin, 2000). This is about to change. Research interest in maintenance for digitalised manufacturing has exploded and maintenance is now on the strategic agenda of many industrial companies. It is considered an increasingly important component in facilitating digitalised manufacturing (McKinsey Global Institute, 2016). Understanding the necessary change, or even the necessary innovation, for preparing maintenance organisations for the demands of digitalised manufacturing, requires a look back at how the application of maintenance has evolved over the years.

Maintenance was not a major concern before 1950. Most industrial work was manual and the equipment was simple needing, at most, a little cleaning and lubrication. If something broke, the operator running the machine would repair it. Reactive maintenance was the standard at this time. Systems often exceeded capacity and equipment failure did not affect production output that much (Peng, 2012).

After the 1950s, industry transformed from being mostly manually operated to including a higher number and complexity of machines; a means of increasing the capacity and efficiency of a production system. Equipment failures came to have a critical impact on production performance and the idea of preventive maintenance (PM) was born. Maintenance tasks were carried out at scheduled times by an organised maintenance organisation, aiming to extend the lifetime of equipment and reduce unscheduled downtime. However, too much PM causes inefficiency in production. Maintenance then became a trade-off between inefficiency from too much planned downtime spent on PM, or a lack of PM possibly leading to failures and thus unplanned downtime. To reduce the risk of too much PM, condition-based maintenance (CBM) was developed during the 1960s. CBM involves monitoring the condition of the equipment and conducting maintenance tasks when monitored values fall outside a certain limit. The limit is commonly set based on historical data and experience and may be triggered by, say, deviant vibrations in a machine. Even though condition-monitoring technology was developed a long time ago, CBM implementation challenges are still reported. These relate to management support, motivation of co-workers, clear roles and responsibilities, visualisation of goals, follow-up on effects, collaboration between functions and interaction between developers and users (Ingemarsdotter et al., 2021; Bengtsson 2008).

The first computerised maintenance management system (CMMS) was developed during the 1980s. This made it easier to plan and follow up maintenance activities. Since the 2000s, there has been a stream of research focusing on technology development and optimisation models to support decision-making on when to conduct maintenance activities (Bell and Percy (2012), Lee et al. (2021), among others). In particular, there has been strong interest among researchers in predicting failures (for example, Han *et al.* (2021)).

The main mission of maintenance organisations has long been regarded as one of maximising equipment availability at the lowest possible cost (Löfsten, 2000; Ylipää et al., 2017). Hence, research has been devoted to finding the optimal PM intervals to ensure the availability of individual pieces of equipment, whilst keeping down the cost of spares replacement. However, since maintenance is part of the production system (Groover, 2007), the crucial factor is not the availability of individual machines. Rather, it is a case of viewing maintenance from a holistic perspective (Bengtsson and Salonen, 2009). For example, maintenance has been shown to contribute to quality (Muchiri et al., 2011), overall productivity (Gopalakrishnan et al., 2019) and sustainability (Holgado et al., 2020). Also, a lack of maintenance has been seen to occasion indirect costs related to production losses (Al-Najjar, 2007; Salonen and Deleryd, 2011). Production losses may give rise to various costs, including lost revenue due to unsold products, or overtime work needed to catch up on lost production. These are indirect costs which may occur due to substandard maintenance.

A variety of maintenance concepts have been developed, aiming to improve maintenance practice in the industry and exercise a more holistic perspective on maintenance. Some examples include total productive maintenance (TPM) (Nakajima, 1988), value-driven maintenance (VDM) (Haarman and Delahay, 2004), reliability-centred maintenance (RCM) (Smith and Hinchcliffe, 2003), risk-based maintenance (RBM) (Jones, 1995), total quality maintenance (TQMain) (Al-Najjar, 1996) and life-cycle profit (LCP) (Ahlmann, 2002). As an example of the holistic perspective, TPM is a concept based on the fundamentals of continuous improvement and waste reduction (Nakajima, 1988). It aims to improve the function and design of production equipment whist improving overall operational efficiency (Swanson, 2001; Chan et al., 2005) This is achieved with small, autonomous groups, cross-functional collaboration and commitment from each employee (Nakajima, 1988; Chan et al., 2005; Jain et al., 2014).

Over time, the strategic aspect of maintenance has been recognised (Gomes et al., 2021; Salonen and Bengtsson, 2011; Pintelon and Parodi-Herz, 2008; Tsang, 1998) and, faced with digitalisation, interest in maintenance has accelerated. Despite this, there is a gap between academia and industrial practice. Maintenance concepts like RCM and TPM are very little-used in industry (Alsyouf, 2009), due to the challenges of implementation (Chan et *al.,* 2005; Cua et al., 2001). Even less-used are the mathematical optimisation models (Dekker, 1996; Sharma *et al.*, 2011). At best, industrial companies succeed in conducting their PM as planned. However, they are commonly interrupted by a need for CM. Thus, the approach in maintenance practice is still reactive (Ylipää et al., 2017; Jin et al.,2016). Interest in technological challenges has continued to dominate research into maintenance (Roy et al., 2016; Silvestri et al., 2020). Less research effort has been expended on the social and organisational aspects of implementation relevant to real-world practice (Akkermans et al., 2016; Fraser et al., 2015). If maintenance organisations are to be ready for the demands of digitalised manufacturing, this must change.

## 2.4 MAINTENANCE IN DIGITALISED MANUFACTURING

*Smart Maintenance is a concept describing maintenance in digitalised manufacturing. Hence, in clarifying what it means to implement Smart Maintenance, this section is relevant to all three research questions (RQ1, RQ2, RQ3).*

The technologies associated with digitalised manufacturing, such as big data, cyber-physical systems (CPS), the Internet of Things (IoT) and cloud computing (Lu, 2017) have led to advances in the maintenance field. These technologies have been investigated in research used in condition-monitoring of equipment, remote services, modelling wear on components, calculating remaining useful life, prescriptive maintenance and failure prediction (Galar et al., 2015; Grubic and Peppard, 2016; Lee et al., 2015; Li et al., 2017; Roy et al., 2016, Matyas et al., 2017; Han et al., 2021; Lu et al., 2021). The aim is to reduce equipment downtime and increase productivity. Predictive maintenance has received much attention from researchers and industry practitioners. They aim to foresee breakdowns by detecting data anomalies, which may provide early warning signs of equipment failure (Compare et al., 2020; Selcuk, 2017). This creates opportunities for taking action before a failure occurs and allows maintenance measures to be planned well in advance, considering resource allocation, spare parts, impact on production and so on. Predictive maintenance has the potential to decrease downtime by 30-50% and increase the operational life of equipment by 20-40% (McKinsey, 2015). It makes predictive maintenance one of the highest-ranked business cases in digitalised manufacturing (McKinsey Global Institute, 2016). Much ongoing research effort is expended on diagnostic and prognostic algorithms, augmented reality (AR) for remote support and so on. In other words, technology-driven efforts. However, if they are to take advantage of these new technologies and keep up with advancements in digitalised manufacturing, entire maintenance organisations need to develop accordingly (Akkermans et al., 2016; Bokrantz et al., 2020c). Technological development is far ahead and too little research has been devoted to the organisational development needed to make maintenance organisations fit for the digital environment (Silvestri et al., 2020).

Just like digitalised manufacturing, maintenance in digitalised manufacturing has been explained and described as a variety of concepts; predictive maintenance (Carnero, 2005), e-maintenance (Lee et al., 2006; Muller et al., 2008), prognostics and health management (PHM) (Lee et al., 2014), Maintenance 4.0 (Kumar and Galar, 2018) and Smart Maintenance (Munzinger et al., 2009; Bokrantz et al., 2020c). Reviews by Bokrantz *et al.* (2020c) and Huang *et al.* (2020) conclude that there is an overlap in these suggested concepts, with varied terminology describing similar things. Effecting change and gaining the support of an entire maintenance organisation means specifying the intended aims exactly (Mento et al., 2002). Thus, it is important to have a clear picture of what maintenance in digitalised manufacturing is. Further, there is a clear advantage in the concept being empirically grounded, as this makes implementing it relevant to the industrial environment (Bokrantz et al., 2020c; Fraser et al., 2015). Thus, this thesis will henceforth refer to maintenance in digitalised manufacturing as "Smart Maintenance", "*an organizational design for managing the maintenance of manufacturing plants in environments with pervasive digital technologies*" (Bokrantz et al., 2020c).

Smart Maintenance is grounded in solid empirical study and supported by research in the area, describing how it is anticipated that maintenance organisations will work in digitalised manufacturing. This is summarised in four dimensions characterising Smart Maintenance: (1) data-driven decision-making, the extent to which maintenance decisions are based on collected, quality-assured and analysed data; (2) human capital resource, the collective knowledge, skills and abilities relevant to the maintenance organisation. Besides traditional practical maintenance skills, this also includes other specific skills (such as data analytics), as well as generic skills (such as communication); (3) internal integration, the degree to which the maintenance function is uniform across the entire plant organisation. This means that the maintenance function and its processes are well-synchronised with the rest of the plant organisation and have smooth cross-functional collaboration; (4) external integration, the extent to which the maintenance function has close contact with parties outside the plant through, say, networks and strategic partnerships (Bokrantz et al., 2020c). These four dimensions of Smart Maintenance can be measured by an empirically validated measurement instrument (Bokrantz et al., 2020a). Such a measurement instrument allows assessment, benchmarking and longitudinal evaluation of Smart Maintenance within and across organisations and may help find further areas for improvement. Still, the next question arises: What is required for the implementation of Smart Maintenance?

Investment in tangible (such as technology) and intangible (such as competence) resources are required for the implementation of maintenance in digitalised manufacturing (Silvestri *et al.*, 2020; Jasiulewicz-Kaczmarek et al., 2017). However, maintenance has been (incorrectly) seen as a "necessary evil" and a cost that should be minimised (Alsyouf, 2007; Salonen and Deleryd, 2011; Al-Najjar and Jacobsson, 2013). Too little has been invested in maintenance (Alsyouf, 2009), as it is difficult to raise money for maintenance-related investment. Profitability calculations are commonly the major decision-support for investment in many companies. These include the annuity method, net present value (NPV), internal rate of return and the payback method (Nilsson and Persson, 1993). Many research attempts have been made to quantify the positive effects of maintenance and support investment suggestions. Examples include Al-Najjar (2007); Lee (2008); Tam and Price (2008); Löfsten (1999); Haarman and Delahay (2004); Marais and Saleh (2009); Naughton and Tiernan (2012). However, a paradox of maintenance is that its effects are deferred and usually not within the normal payback-time criteria. This is also a criticism of the payback method, as it lacks any benefits beyond the payback period (Lefley, 1996). Moreover, intangible benefits seldom match common investment criteria (Irani et al., 1997) and some financial evaluations assume that taking no action carries no cost (Michael and Millen, 1985). This can result in hidden costs related to inefficiency (Roda and Macchi, 2018). Meanwhile, it is also necessary to consider complementary investment. For example, investment that generates more maintenance data requires complementary investment, such as dedicated resources (Marttonen-Arola et al., 2020) and investments in human recourse (such as skill development or recruitment) (Bokrantz et al., 2020b). Hence, domain experts in the manufacturing industry have a major role in identifying the opportunities and challenges of different technology investments and their impact on the manufacturing system. It is not simply about considering technological specifications (McAfee and Brynjolfsson, 2012).

Performance indicators (PIs) are commonly used in industry to manage different operations and resources including follow-up and control actions based on quantitative information (Neely et al., 1995). The purpose of performance measurement is to follow certain measurements and compare them to targets or expectations (Zairi, 1994; Ahmad and Dhafr, 2002; Rouse and Putterill, 2003). This helps determine necessary actions for increasing effectiveness and efficiency (Neely et al., 1995). For a production system, this means producing an intended good or product through well-utilised resources. In other words, with minimum waste of time and effort. PIs are also used to manage maintenance and follow up its performance (Muchiri et al., 2011). For maintenance of production systems, performance is divided into internal efficiency and external effectiveness. This relates to what is done within a maintenance organisation and how that affects the production system (Bokrantz et al., 2020b; Bengtsson and Salonen, 2016). There is an established industrial standard of maintenance PIs, EN 15341 (CEN, 2007), consisting of over 70 PIs divided into three categories: (1) technical, (2) economic and (3) organisational indicators. There are also several maintenance PIs suggested in the research literature (see, for example, Simões et al., (2011)) which are categorised slightly differently by researchers. For example, Kumar et al. (2013), divides PIs into four categories: (1) financial, (2) human resources, (3) indicators related to the internal process and (4) technical indicators. Parida and Chattopadhyay (2007) divide PIs into seven categories: (1) equipment-related indicators, (2) maintenance task-related indicators, (3) cost-related indicators, (4) impact on customer satisfaction, (5) learning and growth, (6) health, safety, security and environment (HSSE) and (7) employee satisfaction.

Most indicators used for maintenance within the industry are related to the internal efficiency of maintenance (Parida and Kumar, 2006). This includes PIs such as mean time to restoration (MTTR), maintenance cost and the ratio of reactive and preventive maintenance tasks. They neglect, or at least give too little attention to, how these PIs influence the performance of a production system (for example, the number of products produced). It is common to accumulate a lot of PIs, believing that more PIs will provide more information for making the right decisions. Rather, it is understanding the relationship between a selection of correctly interpreted PIs that provides opportunities for informed decision-making (Rodriguez et al., 2009; Kang et al., 2016b). With a high number of cause-effect relationships between PIs, a seemingly small change somewhere may lead to effects in other areas (Carlson and Sakao, 2020; Alsyouf, 2006). Balanced scorecards (BSC) have been suggested as a way of linking operational PIs to company strategy and thus visualising these interrelations. The aim of this is to produce a holistic approach to maintenance PIs (Tsang et al., 1999; Kumar et al., 2013), as having a holistic approach to them is particularly important in Smart Maintenance. The effects of Smart Maintenance are anticipated to extend far beyond the traditional PIs of internal efficiency (ratio of corrective and preventive maintenance, MTTR and so on). They are anticipated to impact external effectiveness, such as a firm's manufacturing performance, financial performance and even increased competitiveness (Bokrantz et al., 2020b). With a change in what is expected from the maintenance organisation, there is also a need to review and possibly revise the set of PIs used (Braz et al., 2011; Simões et al., 2016).

The traditional view of maintenance organisations and their role is that of repairing equipment (Ylipää et al., 2017) and the main interest in maintenance research relates to technological challenges (Roy et al., 2016; Silvestri et al., 2020). The same also applies to maintenance management, particularly maintenance management in the context of digitalised manufacturing (Kłos and Patalas-Maliszewska, 2018; Bodo et al., 2020; Ashjaei and Bengtsson, 2017; Blaszczyk and Wisniewski, 2019). Further, maintenance management is commonly assessed by using maturity models with criteria pre-defined by the researchers (Kans 2010; Macchi et al., 2017; Mehairjan et al., 2016; Nemeth et al., 2019; Oliviera and Lopes, 2020); many criteria in assessing maintenance management in digitalised manufacturing are related to technology usage. However, leadership is a central part of organisational change (Battilana et al., 2010; Stouten et al., 2018) and the same applies to the change in Smart Maintenance management (Bokrantz et al., 2020b); an as-yet seldom-explored area dealing with how to lead a maintenance organisation in change.

To sum up, there are factors influencing how Smart Maintenance is adopted by organisations. These factors may either facilitate or inhibit implementation (Akkermans et al., 2016; Bokrantz et al., 2020b). A lack of user-friendliness and openness of the technology, a reluctance to invest and a culture characterised by resistance to change are some factors that make Smart Maintenance implementation difficult (Bokrantz et al., 2020b); in similar vein to the implementation challenges reported for TPM and CBM (Chan et *al.,* 2005; Cua et al., 2001; Ingemarsdotter et al., 2021; Bengtsson, 2008). Leadership is also an important aspect and a central part of organisational change (Battilana et al., 2010; Stouten et al., 2018). Hence, such factors become important in developing a holistic maintenance strategy (including technological, human and organisational aspects) for the implementation of all four dimensions of Smart Maintenance (Bokrantz et al., 2020c).

## 2.5 MAINTENANCE STRATEGY DEVELOPMENT

*This section provides the theoretical background relevant to RQ3 that aims to develop a strategic approach to Smart Maintenance implementation.*

Strategy is a term with a variety of definitions (Mintzberg et al., 1999) but could be described simply as "*a unique and valuable position, involving a different set of activities*" (Porter, 1996, pp. 68). A sequence of well-planned activities should help in achieving a defined goal whilst highlighting priorities in an organisation. By defining strategy as "*a pattern in a stream of decisions*" (Mintzberg and Waters, 1985, pp. 257), it should thus also provide guidance in unpredictable situations (Mintzberg et al., 1999). A maintenance strategy has no clear definition but is commonly associated with a plan for how equipment should be maintained and repaired. In maintenance strategies, this has been reflected as a choice between corrective (CM), preventive (PM) and condition-based maintenance (CBM) (Al-Najjar and Alsyouf, 2003; Bevilacqua and Braglia, 2000; Gutschi et al., 2019; Shyjith et al., 2008; Tan et al., 2011; Wang et al., 2007). This type of strategy is developed using a top-down approach, based on mathematical calculations to evaluate the most cost-efficient equipment repair based on overall business goals. In linking maintenance to overall business goals, it is important to consider maintenance from a strategic perspective, but culture and organisational structure (Bengtsson and Salonen, 2009; Tsang 2002), plus knowledge and skill development (Tsang, 1998) should also be included. Some models describe how to develop such maintenance strategies. See, for example, Salonen (2011), Tsang (1998) and Rastegari and Salonen (2015). These models suggest creating work procedures for identifying the strategic goals of an entire company, linking these goals to the maintenance organisation, identifying relevant PIs to follow them up, assessing the current state and setting targets for PIs and then creating an action plan accordingly. More specifically, Salonen (2011) proposes a strategy document structured as: (1) strategic alignment (in other words, linking company goals to the maintenance organisation); (2) strategic PIs for the maintenance organisation (defining PIs, assessing the current status and setting targets for each PI); and (3) a strategic action plan, including time-specific actions considering human resources, technology and organisation. This structure is proposed to support communication with a company's board. Even though the maintenance strategy and associated goals are linked to the overall company strategy, there are commonly difficulties in linking overall goals to those of individuals (Tsang, 1998), meaning the goals of maintenance employees.

Roadmapping is a method for formulating strategy. It is becoming increasingly popular as it enables effective visualisation and communication (Elbanna et al., 2016; Phaal and Muller, 2009; Ghobakhloo, 2018). A strategy and roadmap must be developed bearing in mind a company's characteristics, such as competencies, goals, priorities and budget (Ghobakhloo, 2018). There is increased research interest in how to align roadmapping with overall company strategy (de Alcantara and Martens, 2019).

In general strategy development, a mixture of top-down and bottom-up approaches has been proposed in which managers and operational employees are formally or informally involved in strategy formulation (Jarzabkowski et al., 2007; Mintzberg and Waters, 1985). The top-down approach is used in determining the direction of development, while the bottom-up approach allows employees to influence their daily work and act on uncertainties. This strategy is dynamic, in that it reflects what is done in practice and evolves with the development of the organisation (Jarzabkowski et al., 2007; Whittington, 2004). How a strategy evolves is captured in Skinner's (1969, pp. 138-139) definition of manufacturing strategy: "*A company's competitive strategy at a given time places particular demands on its manufacturing function and, conversely, that the company's manufacturing posture and operations should be specifically designed to fulfill the tasks demanded by the strategic plan*". A strategy should, therefore, not be static but be adapted as needed.

To summarise, there is much useful knowledge from research into maintenance strategy development and general strategy development. Despite this, too many industrial companies lack a formal, communicated maintenance strategy (Alsyouf, 2009; Cholasuke et al., 2004). Holistic maintenance strategies that consider organisational structure and organisational development are important aspects of implementing Smart Maintenance (Bokrantz et al., 2020c), as is guidance from research that supports industrial maintenance organisations in their development (Silvestri et al., 2020) towards meeting the demands of digitalised manufacturing.

## 2.6 SUMMARY

Change is underway within the manufacturing industry and maintenance organisations need to develop accordingly (Akkermans et al., 2016; Bokrantz et al., 2020c). Interest in maintenance has accelerated over the last decade and much technology-driven research has been conducted, aimed at foreseeing failures and reducing equipment downtime (Galar et al., 2015; Grubic and Peppard, 2016; Lee et al., 2015; Li et al., 2017; Roy et al., 2016). However, digitalisation in general, and Smart Maintenance in particular, is not limited to technology. Organisational change needs to be taken into account, including such factors as strategy, leadership, culture, dedicated resources and organisational structures (Balakrishnan and Das, 2020; Bokrantz et al., 2020b; Gürdür et al., 2019). There is no single recipe for implementing Smart Maintenance that fits all companies. However, there is a need for guidance from research which supports maintenance organisations in their development and keeps change ongoing (Silvestri et al., 2020; Stouten et al., 2018). There is a clear research gap regarding how to support organisational development and organisational innovation in maintenance; a gap which this thesis intends to fill.

# 3
# RESEARCH APPROACH

*Beliefs and previous experience will influence all decisions faced by human beings. The same applies to the choices and decisions made in research. This chapter explains the research approach of this thesis, including epistemological assumptions, the mixed-methods approach that has been applied and an overview of the research design and methods used in the thesis' six studies.*

## 3.1 EPISTEMOLOGICAL ASSUMPTIONS

Ontological and epistemological beliefs, how we see the world and what we consider to be truth, varies between people (Knowles, 2006). These beliefs have an impact on the choice of methodological approach and methods (Guba and Lincoln, 1994; Crotty, 1998). This means that my preferences and how I see the world have influenced the choice of research design and the methods of conducting the research presented in this thesis.

I aim to contribute to the maintenance research field and inspire industry practitioners to use what has been developed through research, whilst striving for rigorous research that has practical relevance (Schultz, 2010; Vermeulen, 2005). In terms of relevance, the right questions need to be asked. Regarding rigour, the right type of method must be carefully selected and executed (Vermeulen, 2005). The research questions in this thesis have evolved from real-world problems, with the research conducted in an industrial setting to ensure practical relevance. With production systems regarded as an interplay of people, equipment and procedures, organised in a particular order to transform tangible inputs (raw materials, semi-finished goods) and intangible inputs (knowledge, information) into outputs of goods or services (Bellgran and Säfsten, 2009; Groover, 2007), it has been important to also involve industry practitioners in the research. Further, the world is complex and I strongly believe that rigorous research into real-world implementation requires multiple methods. Thus, this thesis has adopted a mixed-methods approach (Creswell, 2013), with methods selected depending on the problem being addressed (Creswell and Plano Clark, 2018).

## 3.2 RESEARCH APPROACH

A mixed-methods approach was chosen because it allows broad and deep investigation through a combination of quantitative and qualitative methods (Creswell, 2013). A total of six studies were conducted to answer the three research questions in this thesis. Figure 1 provides an overview of how each of the studies and associated appended papers contributes to the three research questions, plus a timeline for the studies.

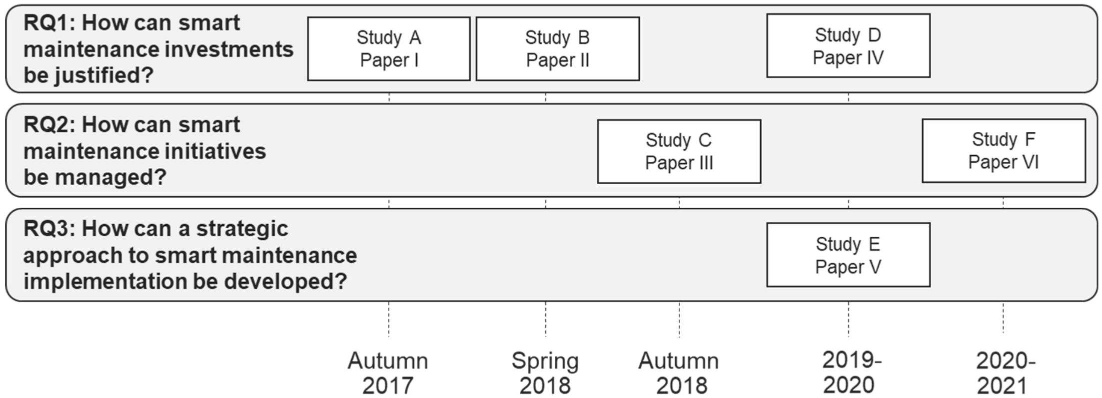


Figure 1: Overview of how the studies relate to each research question.

The results of the research presented in this thesis have emerged by iterating theoretical and empirical studies. The research process and the contribution of the studies are best explained by considering the research questions in a sequence.

### RQ1 – How can Smart Maintenance investments be justified?

The digitalisation of the manufacturing industry is a technological shift in that technological investment is needed. The importance of maintenance has been acknowledged in both theory and practice. Despite this, not enough has been invested in maintenance. Hence, I wanted to investigate what research has previously been conducted but also to study the investment process from an industrial perspective. RQ1 is answered by Studies A, B and D.

Study A (Appended Paper I) was a theoretical study aimed at gaining an overview of research into maintenance models and thus highlighting the effects of maintenance. Quantification is one way of describing the benefits of maintenance, or the consequences of a lack of it. Thus, it is valuable to know whether/how these models can support Smart Maintenance investments. Study B (Appended Paper II) was an empirical study aimed at identifying influences on maintenance-related investment. The investment process commonly affects many parties in an organisation, not just the maintenance function. This study aimed to explore and gather an in-depth understanding of the maintenance-related investment process and its influences in an industrial setting. Study D (Appended Paper IV) was an empirical study, aiming to determine how industry practitioners project the impact of new technology (in this case, 5G technology) on manufacturing performance. The study shows a concrete example of how to evaluate new technology and its impact on performance, including maintenance performance and may be useful in justifying investment in new technology.

### RQ2 – How can Smart Maintenance initiatives be managed?

Despite the above, investment in technology does not provide all the answers. A maintenance organisation needs to develop if it is to use technology to its full potential. The effects of initiatives taken need to be followed up and someone needs to lead the development. One theoretical study (Study C) and one empirical study (Study F) were carried out to provide answers to RQ2, on how to manage Smart Maintenance initiatives.

The aim of Study C (Appended Paper III) was to determine whether currently available maintenance performance indicators (PIs) may be used to follow up on the anticipated effects of Smart Maintenance. This was a theoretical study, in which PIs collected from the literature were analysed using a deductive approach to describe what the PIs measure. Are these PIs sufficient to follow up the anticipated effects of Smart Maintenance and control Smart Maintenance initiatives? By contrast, Study F (Appended Paper VI) was an explorative, empirical study, investigating how maintenance managers perceive leadership in maintenance when faced with pervasive digitalisation.

### RQ3 – How can a strategic approach to Smart Maintenance implementation be developed?

Structured development of a maintenance organisation is best achieved by being packaged in a strategic approach. RQ3, on how to develop a strategic approach to Smart Maintenance implementation, is answered by one empirical, qualitative study; Study E.

Study E (Appended Paper V) was conducted to gain deep insight into the development of maintenance strategies in industry. The study was essentially empirical but included theoretical insights into strategy development (aiming to use insights from research into general strategy development). The empirical basis of the study aimed to gain deep insights into industry practice, thus ensuring the industrial applicability of strategy development to Smart Maintenance implementation.

Moreover, the DOI theory was used for theoretical interpretation of the results of the six studies answering the three research questions. This entailed seeing Smart Maintenance from the perspective of organisational innovation, to further describe and understand how to facilitate Smart Maintenance implementation.

## 3.3 RESEARCH DESIGNS AND METHODS

In conducting this research and bearing in mind my epistemological assumptions, a variety of research designs and methods were used. In other words, a mixed-methods approach. Table 2 provides an overview of the six studies, including the associated research design and methods of data collection and data analysis. Detailed descriptions are available in each of the appended papers.

Table 2: Overview of research design and methods.

| Study/ Paper | Classification | Research design | Data collection methods | Data analysis methods | Validation techniques |
|---|---|---|---|---|---|
| Study A Paper I | Theoretical | Literature study | Documents | Categorisation inspired by constant comparison | Negotiated agreement |
| Study B Paper II | Empirical | Multiple-case study including three industrial cases | Semi-structured interviews Documents | Coding using data structures | Peer debriefing |
| Study C Paper III | Theoretical | Literature study | Documents | Coding using a pre-defined coding scheme | Intercoding reliability<br><br>Negotiated agreement |
| Study D Paper IV | Empirical | Mixed-methods including eight industrial demonstrators | Semi-structured interviews Documents | TOPSIS method (quantitative data) Open coding (qualitative data) | TOPSIS for robustness |
| Study E Paper V | Empirical | Multiple-case study including three industrial cases | Questionnaires Participant observations Documents Focus group | Open coding | Peer debriefing |
| Study F Paper VI | Empirical | Interview-study | Semi-structured interviews | Thematic analysis followed categorisation using a socio-technical systems framework | Peer debriefing |

### Study A

In Study A (Appended Paper I), a literature study was conducted to shed light on the research into methods and models for planning, evaluating or quantifying maintenance work (contribution to RQ1). The literature search was done in Scopus, with references tracked as a complementary method of finding additional relevant publications. Title, abstract and conclusions were studied and the words “model”, “method”, “costs”, “losses”, and “quantify” in combination with “maintenance” were considered for the selection. Thirty-five (35) publications were selected and the models described in each publication were analysed and categorised inductively using a method inspired by constant comparison (Glaser and Strauss, 1967). The main contribution of Study A is an overview of maintenance models for quantifying or describing the effects of maintenance.

### Study B

Study B (Appended Paper II) was designed as a multiple-case study (Barratt *et al.*, 2011; Yin, 2018), including three industrial cases to study the process of maintenance-related investment (contribution to RQ1). The three cases were from different industries; discrete-part manufacturing, continuous manufacturing and infrastructure and traffic service. All cases were selected from Swedish industry. For each case, an investment to study was selected based on five criteria: (1) done for maintenance purposes, (2) associated with short-term cost and long-term savings (3) financial analysis, including costs and anticipated savings (4) process was documented, (5) possibility to interview those involved in the investment. A total of 12 semi-structured interviews were conducted face-to-face (Irvine et al., 2013). These interviews were audio-recorded and transcribed and then coded using NVivo software. The coding structure was based on data structures inspired by Gioia et al. (2013) for transparency purposes (Ketokivi and Choi, 2014). Documentation on the investment was collected for triangulation purposes (Denscombe, 2014; Yin, 2018). The main contribution of Study C is a set of factors influencing the maintenance investment process.

### Study C

In Study C (Appended Paper III), a literature study was conducted to identify performance indicators (PIs) relevant to maintenance activities (contribution to RQ2). The aim of the literature study was not a full review of the research literature but, rather, to create a list of PIs for use in further analysis. Data saturation was achieved with the six selected publications. From these six publications, 170 PIs were analysed by deductive coding (NVivo software). Two equally knowledgeable researchers coded the 170 PIs using a procedure based on intercoder reliability and negotiated agreement (Campbell et al., 2013). Further, for clarification purposes, an inductive approach inspired by constant comparison (Glaser and Strauss, 1967) was used to analyse the PIs coded as *other* in the pre-defined coding scheme. The main contribution of Study B is a categorisation of the maintenance PIs, to support quantitative follow-up of the effects of Smart Maintenance.

### Study D

In Study D (Appended Paper IV), a mixed-methods approach was used to determine the anticipated impact of 5G technology on manufacturing performance, including maintenance performance (contribution to RQ1). The study was based on eight industrial demonstrators (demos) implemented at two manufacturing plants (two different companies), whose aim was to demonstrate the use of 5G technology on industrial shop-floors. Four industry practitioners projected the impact of 5G technology and the industrial demos on manufacturing performance. Both quantitative and qualitative data was collected. The quantitative data analysis was based on the TOPSIS method (Hwang and Yoon, 1981), modified for a systematic and robust evaluation of 5G characteristics and their impact on specific performance indicators. The qualitative data was collected and analysed to gain a deeper understanding of the value of 5G technology in manufacturing generally and for the eight demos in particular. The main contribution of Study D is a demonstration of evaluating new technology. For this particular study, that meant how 5G technology and its key characteristics impact manufacturing performance in different industrial applications.

### Study E

Study E (Appended Paper V) was designed as a multiple-case study (Barratt *et al.*, 2011; Yin, 2018), exploring the phenomena of Smart Maintenance strategy development (contribution to RQ3). Purposive sampling (Palys, 2008) was used to select cases in which empirical data on strategy development could be gathered. The sampled cases needed to fulfil three criteria; they must have: (1) an organisational unit responsible for equipment maintenance, (2) dedicated resources to develop Smart Maintenance strategies and (3) willingness to participate. Three cases were sampled; one from discrete-part manufacturing, one from continuous manufacturing and one from infrastructure and traffic service. All were from Swedish industry. Several methods were used for data collection; questionnaires based on the questions from the four within-factor models reported in Bokrantz et al., (2020a) for qualitative data, plus participant observations, documents and focus groups for qualitative data. An inductive approach was used to analyse the qualitative data. The collected data was analysed iteratively using an open coding procedure, inspired by constant comparison (Glaser and Strauss, 1967). The main contribution of Study D is a strategy development process for Smart Maintenance implementation.

### Study F

In Study F (Appended Paper VI), 20 explorative interviews were conducted. The interviewees were selected using purposive sampling (Palys, 2008), with experience of leadership in industrial maintenance within manufacturing. All interviewees were recruited through membership of a Swedish professional interest organisation focusing on sustainable maintenance management. An in-depth description of the sampling and methodology was offered using consolidated criteria for reporting qualitative research (COREQ) (Tong et al., 2007). Two open-ended questions were asked during the interviews. All interviews were audio-recorded and transcribed, resulting in 213 A4 pages of qualitative data (approximately 115,000 words in Swedish) about real-life experiences of leadership in industrial maintenance. The transcriptions were inductively analysed, based on a thematic analysis (Braun and Clarke, 2006) and resulting in main themes from the interviews. A deductive approach was then used to categorise the main themes based on a socio-technical systems (STS) framework (Davis et al., 2014). The main contribution of Study F is a consideration model of leadership in maintenance faced with pervasive digitalisation.

# 4

# RESEARCH RESULTS

*This chapter presents the results of the studies in the six appended papers, focusing on their contribution to the research questions. The chapter is divided into three sections, one for each research question, as shown in Table 3.*

Table 3: Overview of the appended papers and their contribution to the RQs.

| Section | Appended Paper | Main contribution |
|---|---|---|
| **4.1 Justifying Smart Maintenance investments (RQ1)** | Appended Paper I | Identification and categorisation of maintenance models for planning, evaluating or quantifying maintenance work. |
| | Appended Paper II | Identification of influences on maintenance-related investments. |
| | Appended Paper IV | Determination of the projected impact of new technology (in this case, 5G technology) on manufacturing performance. |
| **4.2 Managing Smart Maintenance initiatives (RQ2)** | Appended Paper III | Mapping of industrial maintenance performance indicators in relation to the anticipated effects of Smart Maintenance. |
| | Appended Paper VI | Overall consideration model for maintenance leadership in digitalised manufacturing. |
| **4.3 Strategic approach to Smart Maintenance implementation (RQ3)** | Appended Paper V | Proposed strategy development process for Smart Maintenance implementation. |

## 4.1 JUSTIFYING SMART MAINTENANCE INVESTMENTS

*This section presents the results of RQ1: How can Smart Maintenance investments be justified? The RQ is answered by Appended Papers I, II and IV.*

### Quantifying effects of maintenance (Appended Paper I)

The aim of Appended Paper I was to identify maintenance models for planning, evaluating, or quantifying maintenance work. A literature study was conducted to review how the effects of maintenance may be quantified using models developed in research. It also provided valuable knowledge on whether/how these models can support Smart Maintenance investments (thus contributing to RQ1). The literature study resulted in the selection of 35 publications, describing 24 different models (further details in Appended Paper I). The models in the publications were analysed and then categorised inductively using a method inspired by constant comparison (Glaser and Strauss, 1967) in which six different categories emerged: (1) economic value, (2) categorisation of maintenance losses, (3) cost and cost-effectiveness associated with maintenance activities, (4) overall management, (5) function-orientated planning and (6) simulation and maintenance. Depending on the aim, a model could be selected from one of the categories to provide structured support and to map and communicate the benefits of maintenance. Table 4 gives an overview of the categories and the number of models within each one. Please see Appended Paper I for detailed reading about the maintenance models.

Table 4: Overview of different categories of models for quantifying, evaluating or planning maintenance work. Table based on results from Appended Paper I.

| **Category** | **Number of models** | **Sample references** |
|---|---|---|
| Cost and cost-effectiveness associated with maintenance activities | 10 | Al-Najjar and Alsyouf (2003)<br>Wu et al. (2015) |
| Economic value | 4 | Haarman and Delahay (2004)<br>Marais and Saleh (2009) |
| Function-orientated planning | 4 | Rausand (1998)<br>Khan and Haddara (2003) |
| Categorisation of maintenance losses | 3 | Yamashina and Kubo (2002)<br>Salonen and Deleryd (2011) |
| Overall management | 2 | Nakajima (1988)<br>Sherwin (2000) |
| Simulation and maintenance | 1 | Alabdulkarim and Ball (2013)<br>Alrabghi and Tiwari (2015) |

### Influences on maintenance-related investments (Appended Paper II)

Appended Paper II aimed to identify influences on maintenance-related investments. A multiple-case study with three industrial cases was conducted to study the process of maintenance-related investments and identify its influences. A total of 12 semi-structured interviews were conducted, including questions relating to the practicalities of the investment process. The interviews were audio-recorded and transcribed, then further analysed (for each case) using data structures inspired by Gioia et al. (2013). The analysis resulted in a set of factors influencing the investment process (thus contributing to RQ1). How the data was interpreted to discover influencing factors (the data structures) can be seen in Appended Paper II. The factors identified in each case are listed below.

Six influencing factors were identified in Case 1:

- fact-based decision-support,
- internal integration,
- foresight,
- well-defined investment process,
- communication,
- step-by-step evaluation.

Eight influencing factors were identified in Case 2:

- company culture,
- internal integration,
- fact-based decision-support,
- innovative thinking,
- foresight,
- external factors (such as laws and regulations),
- competence,
- transparency.

Four influencing factors were identified in Case 3:

- fact-based decision-support,
- foresight,
- internal integration,
- well-defined investment process.

A total of 11 influencing factors were identified from the three cases, of which three factors were common to all cases: 1) fact-based decision-support, 2) internal integration and 3) foresight. All cases emphasised the importance of making decisions based on facts and preferably including quantitative arguments and calculations. While all cases showed a need for calculations as decision support, Case 2 had no strict investment criteria, as shown in Cases 1 and 3. Still, fact-based decision-support was a common factor across all cases, as was internal integration. In all cases, the preparatory work for an investment proposal and decisions involves many people collaborating and sharing information to quality-assure the decision-support. Further, the right decision-support can aid internal integration in some parts of an organisation by offering a shared view of why maintenance investment is needed. The third common factor across the cases was foresight. This means it is easier to get a proposal approved if there is financial room for it in the investment budget; in other words, if the need for investment is brought up before the investment budget is set. Investment proposals that cropped up unexpectedly would usually be queried and probably postponed.

The factors from the cases differed a little in their characteristics. Case 1 and Case 3 focused much more on the formal investment process. This included such factors as having a well-defined investment process (Cases 1 and 3) and step-by-step evaluation (Case 1). By contrast, factors such as company culture, transparency and innovative thinking were identified in Case 2. The 11 factors identified in the three cases are listed in Table 5.

Table 5: The 11 influencing factors identified in the three cases.

| **Influencing factor** | **Case 1** | **Case 2** | **Case 3** |
|---|---|---|---|
| Fact-based decision-support | x | x | x |
| Internal integration | x | x | x |
| Foresight | x | x | x |
| Well-defined investment process | x | | x |
| Communication | x | | |
| Step-by-step evaluation | x | | |
| External factors | | x | |
| Company culture | | x | |
| Transparency | | x | |
| Competence | | x | |
| Innovative thinking | | x | |

### Impact of 5G technology in the manufacturing industry (Appended Paper IV)

Appended Paper IV aimed to determine the anticipated impact of using 5G technology in the manufacturing industry. The study was based on eight industrial demonstrators (demos) with a pilot installation of 5G technologies on the shop-floor at two manufacturing plants (two different companies). Four industry practitioners with manufacturing expertise and experience in 5G technology projected the impact of 5G technology on manufacturing performance, in both quantitative and qualitative terms.

The quantitative data was analysed using a modified TOPSIS method. This provided a systematic and robust evaluation of 5G characteristics and their impact on specific performance indicators. The analysis shows how 5G technology is projected to impact manufacturing performance. This, in turn, can be used as justification for investing in the technology (thus contributing to RQ1). Overall, 5G technology is projected to have the greatest impact on productivity, flexibility and maintenance performance. Quality and sustainability are also projected to be affected but to a lesser extent. The 5G technology characteristics expected to be most beneficial are the ability to add more data sources, the low latency and scalability of the network. However, the analysis of individual demos shows a difference between applications regarding important characteristics of 5G technology and their anticipated impact on performance. For example, applications focusing on monitoring, controlling and analysis of data in real-time tend to be more dependent on the characteristic of low latency. Applications including data and information for human operators tend to be more dependent on the characteristic of wide network coverage. Another example is that demos with real-time data analysis (dependent on low latency) are anticipated to impact maintenance performance to a greater extent compared to other demos. Figure 2 shows an example of a graph from one of the demos in Appended Paper VI.

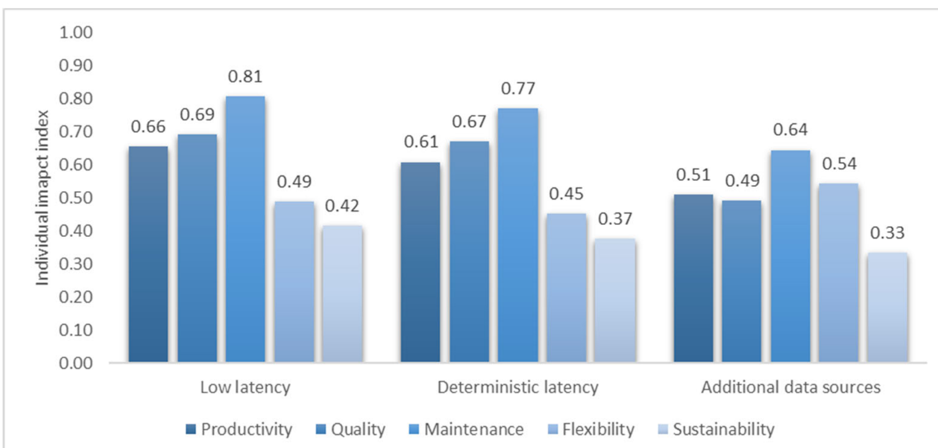


Figure 2: One of the demos from Appended Paper VI is mostly dependent on low latency, deterministic latency and additional data sources. This is anticipated to have a corresponding impact on productivity, quality, maintenance performance, flexibility and sustainability. The figure is adapted from Appended Paper VI.

In this specific demo, low latency, deterministic latency and additional data sources tend to be most important. An individual impact index was calculated (using a modified TOPSIS method) for each 5G characteristic, to determine how these characteristics impact performance, with 0 meaning low impact and 1 meaning high impact. The modified TOPSIS method yielded specific, quantitative results describing how different 5G characteristics and their impact on performance vary between applications. This was summarised simply by one of the participants in the qualitative data (from the interviews with open-ended questions): *"You need to look at different cases [meaning different demos]. They will impact differently"*. For more details of the analysis and its results, please see Appended Paper IV.

### Summary - justifying Smart Maintenance investment

Several models can help quantify or describe the effects of maintenance and justify Smart Maintenance investment (Appended Paper I). Further, various factors influence the investment process, such as fact-based decision-support, internal integration and foresight (Appended Paper II). Awareness of these factors can be beneficial, both in preparing an investment proposal and further along in the decision process. If it is unclear what new technology may bring, a modified TOPSIS method can be used to evaluate different characteristics of that technology in manufacturing performance (Appended Paper IV). For example, it is anticipated that 5G technology, with its low latency, ability to add new data sources and network scalability will impact productivity, flexibility and maintenance performance. Robust evaluation of new technology can help justify Smart Maintenance investment.

## 4.2 MANAGING SMART MAINTENANCE INITIATIVES

*This section presents the results of RQ2: How can Smart Maintenance initiatives be managed? The RQ is answered by Appended Papers III and VI.*

### Performance indicators for Smart Maintenance (Appended Paper III)

Appended Paper III aimed to determine how industrial maintenance performance indicators (PIs) can measure the anticipated effects of Smart Maintenance. It offers a way to manage (control and follow up) Smart Maintenance activities, based on quantitative information. A literature study was done to collect industrial PIs for maintenance. Six publications were selected and, from them, 170 PIs were used for analysis. Two researchers coded the 170 PIs, bearing in mind the anticipated effects of Smart Maintenance. They used intercoding reliability and negotiated agreement to ensure a rigorous coding procedure. Their analysis resulted in a categorisation of maintenance PIs for use in measuring and following up different effects of Smart Maintenance (thus contributing to RQ2). The majority of the PIs (93 out of 170), measured maintenance performance. These PIs typically described failure behaviours/modes and machine repairs. In other words, internal efficiency of the maintenance organisation. Examples of PIs included the mean time to restoration (MTTR) and total downtime. Eleven (11) PIs were coded as “manufacturing performance”, reflecting production system outcomes. In other words, the external efficiency of maintenance. Examples included productivity, cycle time and production rate. Ten (10) PIs were coded as “safety performance”, including such PIs as number of incidents, number of accidents and number of failures causing personal injury. Four (4) PIs related to financial aspects affected by factors other than maintenance actions. Thus, these were coded as “financial performance”. Return on fixed assets (ROFA) and return on maintenance investments are examples of financial performance. Four (4) PIs were coded as “environmental performance”, measuring environmental impacts such as the number of failures causing environmental damage. Three (3) PIs were coded as “job satisfaction”. These included employee turnover and employee satisfaction. None of the PIs were categorised as “organisational attractiveness” or “competitive advantage” and 45 were categorised as “other” as they did not fit any of the pre-defined codes. Figure 3 provides an overview of the coding of the 170 PIs.

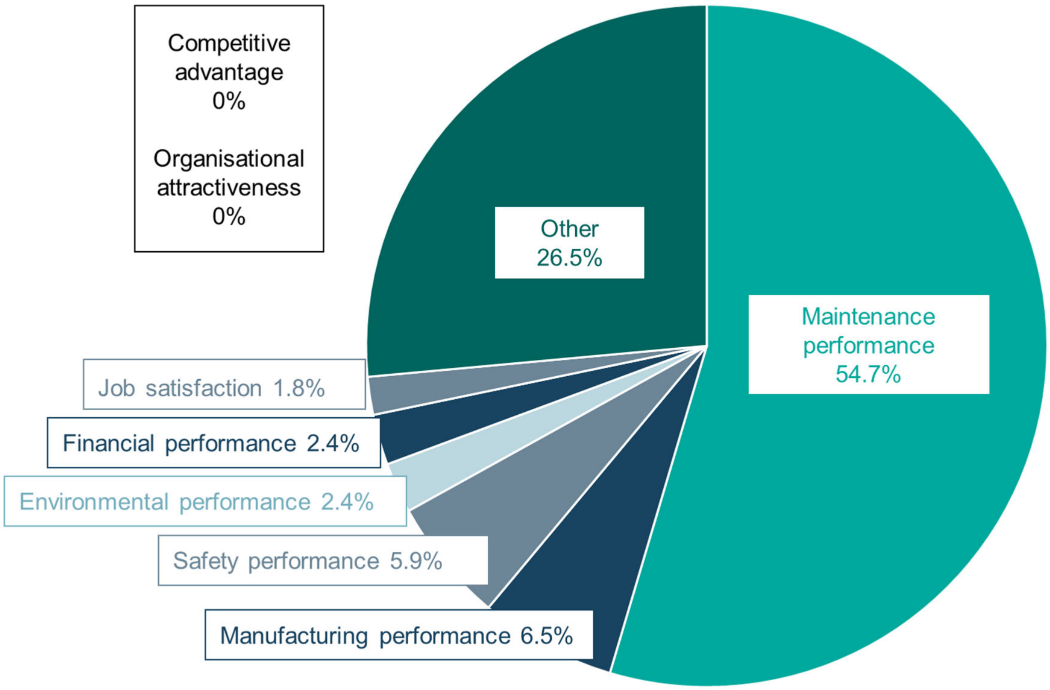


Figure 3: A pie chart providing an overview of how the 170 PIs were coded and percentages of the PIs in each category. The figures are from Appended Paper III.

The 45 PIs from the "other"-category were coded inductively, resulted in five more categories: complementary investments, human capital resource, customer satisfaction, HSSE and organisational. Three PIs remained uncategorised.

To summarise, it is possible to measure most of the effects of Smart Maintenance using current maintenance PIs. These PIs were divided into 13 suggested categories but none covering competitive advantage and organisational attractiveness. This does not necessarily mean these effects cannot be followed up without creation of new PIs. Rather, it means that integration of PIs between functions is needed; this links Smart Maintenance initiatives to performance in aspects other than maintenance performance.

### The changing leadership of industrial maintenance (Appended Paper VI)

Appended Paper VI aimed to describe (from a socio-technical systems perspective) the leadership of maintenance organisations that are faced with pervasive digitalisation. Twenty maintenance managers were given semi-structured interviews. Two open-ended questions were used to get these managers discussing their perception of maintenance leadership; their experiences and projections for the future. The study shows the role of the maintenance manager in changing organisations (thus contributing to RQ2). A thematic analysis was done, from which main themes emerged. It was found that the maintenance managers mainly talked about: 1) observations on change and resistance to change; 2) roles and responsibilities within maintenance; 3) personnel; 4) competence; 5) setting goals; 6) coherence within the organisation; 7) dependencies outside the organisation; and 8) social practices.

Theme *1) Observations on change and resistance to change* covers specific statements about change and potential resistance to it. Theme *2) Roles and responsibilities within maintenance* covers how the maintenance managers perceived the future roles of leader and co-worker. Theme *3) Personnel* describes the concerns about keeping current employees and recruiting new ones to the maintenance organisation. Theme *4) Competence* describes the competency requirements among the leaders and co-workers. Theme *5) Setting goals* describes the goals of the maintenance organisation and their relationship to the overall company and individual co-workers. Theme *6) Coherence within the organisation* describes the collaboration between the maintenance function and other functions. Theme *7) Dependencies outside the organisation* reflects the projected increase in collaboration with parties outside the manufacturing plant. Theme *8) Social practices* describes informal practices relating to interactions between people. Theme *9) Minor themes* was used as an “other” category to avoid force-fitting but these were not analysed further.

The main themes and associated sub-categories are presented in Table 6. The sub-categories give a more detailed view of what the maintenance managers talked about.

Table 6: Emerging main themes and associated sub-categories from the interviews with 20 maintenance managers.

| Main theme | Sub-categories |
|---|---|
| 1. Observations on change and resistance to change | 1.1 Rapid changes<br>1.2 Propensity for change<br>1.3 “Things were better before”<br>1.4 Investments and new technology |
| 2. Roles and responsibilities within maintenance | 2.1 Decision-making<br>2.2 Shared or delegated responsibility<br>2.3 Coaching leadership<br>2.4 Role of the leader<br>2.5 Role of the co-worker |
| 3. Personnel | 3.1 Personnel turnover<br>3.2 Recruitment<br>3.3 Attracting recruits<br>3.4 Young potential recruits<br>3.5 Diversity<br>3.6 Developing personnel |
| 4. Competence | 4.1 Competence of the leader<br>4.2 Competence of the co-worker |
| 5. Setting goals | 5.1 Vision<br>5.2 Strategy<br>5.3 Formulating goals<br>5.4 Progress<br>5.5 Key performance indicators<br>5.6 Individual goals |

| Main theme | Sub-categories |
|---|---|
| 6. Coherence within the organisation | 6.1 Cross-functionality<br>6.2 Maintenance as coordinator<br>6.3 Relationship to operations<br>6.4 Relationship to projects/investments<br>6.5 Relationship to IT<br>6.6 Technological integration<br>6.7 Barriers<br>6.8 Collaboration within the maintenance organisation |
| 7. Dependencies outside the organisation | 7.1 Customer-supplier relations<br>7.2 Research and education<br>7.3 Networks<br>7.4 Benchmarking<br>7.5 Partnerships |
| 8. Social practices | 8.1 Corporate culture<br>8.2 Trust<br>8.3 Experience<br>8.4 Human-centeredness<br>8.5 Processes, practices |
| 9. Minor themes | 9.1 Centralisation of maintenance<br>9.2 Flexibility of the organisation<br>9.3 Role model<br>9.4 Holistic view<br>9.5 Hierarchical structures<br>9.7 Instructions<br>9.8 Self-support<br>9.9 Standardisation<br>9.10 Incremental change<br>9.11 Maintenance plan<br>9.12 Maintenance management system<br>9.13 Vibration technology |

To avoid giving a purely descriptive presentation of the results, the main themes were structured into a socio-technical systems (STS) framework (Davis et al., 2014), including a set of sub-systems: *goals, people, processes/procedures, buildings/infrastructure, technology and culture*. The framework also includes perspectives on an external environment, according to *financial/economic circumstances, regulatory frameworks* and *stakeholders*. Table 7 provides an overview of how the main themes from the interviews relate to the sub-systems of the STS framework; an overall consideration model for leadership in maintenance in digitalised manufacturing. A light grey cell indicates a connection between main theme and sub-system, while a dark grey cell indicates a stronger connection between main theme and sub-system.

Table 7: Overview of main themes and sub-systems in Davis et al.'s (2014) STS framework; an overall consideration model.

| **Main themes** | Goals | People | Processes | Buildings | Technology | Culture | Financial | Regulatory FW | Stakeholders |
|---|---|---|---|---|---|---|---|---|---|
| 1. Observations on change and resistance to change | | ■ | ■ | | ■ | ▒ | ▒ | | |
| 2. Roles and responsibilities within maintenance | | ■ | ■ | | ▒ | | | | |
| 3. Personnel | ▒ | ■ | ▒ | | ▒ | ▒ | | | |
| 4. Competence | | ■ | | | ■ | | | | |
| 5. Setting goals | ■ | ▒ | ▒ | | | | | | |
| 6. Coherence within the organisation | ▒ | ■ | ■ | | ■ | | ▒ | | |
| 7. Dependencies outside the organisation | | ▒ | ▒ | | ▒ | | | | ▒ |
| 8. Social practices | | ■ | ■ | | | ■ | | | |

To summarise the interviews, the maintenance managers spoke mainly about the sub-systems of technology, people and processes. The rapid development of technology is affecting the maintenance organisation. The managers discussed how technology changes processes and work procedures and how it generally sets new requirements of peoples' skills and influences their attitudes to work. The latest technology may attract potential co-workers (especially young people) to start working within maintenance. However, resistance to change is likely to arise among the more conservative people who already work in the maintenance organisation. Hence, maintenance managers need to deal with people from both extremes, as well as those in between. More details of the main themes and their relationships to the sub-systems are provided in Appended Paper VI. However, the overall consideration model describes what is important when leading maintenance in digitalised manufacturing. Maintenance managers need to approach the main themes with particular emphasis on people, processes and technology.

### Summary - managing Smart Maintenance initiatives

Many maintenance PIs can be used to follow up the effects of Smart Maintenance (Appended Paper III). This is a way of managing Smart Maintenance initiatives through suitable follow-up and control activities. Thirteen PI categories were suggested. However, to cover the full range of effects that Smart Maintenance is expected to bring, it is necessary to integrate the use of PIs across functions. The role of the maintenance manager is to lead the maintenance organisation during the change (Appended Paper VI). An overall consideration model describes what is important in leading maintenance in digitalised manufacturing. In a nutshell, the role of a maintenance manager is changing from technical manager to leader of people within an organisation in change.

## 4.3 STRATEGIC APPROACH TO SMART MAINTENANCE

*This section presents the results of RQ3: How can a strategic approach to Smart Maintenance implementation be developed? The RQ is answered by Appended Paper V.*

Appended Paper V aimed to propose a strategy development process for Smart Maintenance implementation. The study was a multiple-case study, in which three industrial companies were followed as they developed Smart Maintenance strategies. First, the current state of the maintenance organisation was determined using a Smart Maintenance measurement instrument. The results were then discussed with each of the case companies, followed by a workshop for suggesting activities and starting to develop a roadmap. The case companies were then asked to continue working with the workshop material; developing and compiling it to a strategy for Smart Maintenance implementation, including a roadmap. The atmosphere, experiences and outcome of discussions were observed during the workshop and recorded as field notes. The companies' Smart Maintenance implementation strategies were also reviewed. The field notes and documented strategies were analysed, with six main themes emerging from the empirical findings. These themes are likely to be important in strategy development, as they were common to all cases: *employee engagement; interplay among the dimensions* (of Smart Maintenance); *internal communication; strategic alignment; planning & scheduling activities*; and *follow-up*. Please see Appended Paper V for details of the analysis in each of the cases. Table 8 provides a summary of the themes and supporting evidence.

Table 8: Summary of emerging themes and their evidence from the three cases.

| Theme | Supporting evidence from the three cases |
|---|---|
| Employee engagement | The results from the Smart Maintenance measurement instrument and associated benchmarking created intense discussions among the employees. For example, they discussed challenges in their current work situation and how they would like to work. |
| Interplay among the dimensions | The data-driven decision-making dimension of Smart Maintenance was initially the focus during the workshop and many associated activities were suggested at the beginning. As the workshop went on, activities relating to the other dimensions of Smart Maintenance were also suggested. Ultimately, all four dimensions of Smart Maintenance were considered in the companies' strategies. |
| Internal communication | The companies devoted much time to internal communication about Smart Maintenance. The material developed during the workshop was further developed for use in communicating with the management group and the employees. |
| Strategic alignment | The goal of Smart Maintenance was clearly connected to the companies' goals. One company in particular linked Smart Maintenance to its established values. |
| Planning & scheduling activities | Activities from the Smart Maintenance roadmap were integrated into the companies' existing plans. |
| Follow-up | Activities and possible effects of Smart Maintenance were integrated into established follow-up routines and thus followed up regularly (monthly). |

The six themes emerging from the cases were interpreted using literature on general strategy development and, from there, a strategy development process for Smart Maintenance implementation was proposed. This process is cyclical and has six steps: 1) benchmarking of the maintenance organisation, 2) setting clear goals, 3) setting strategic priorities, 4) planning key activities, 5) elevating implementation and 6) following up. The proposed process is presented in Figure 4.

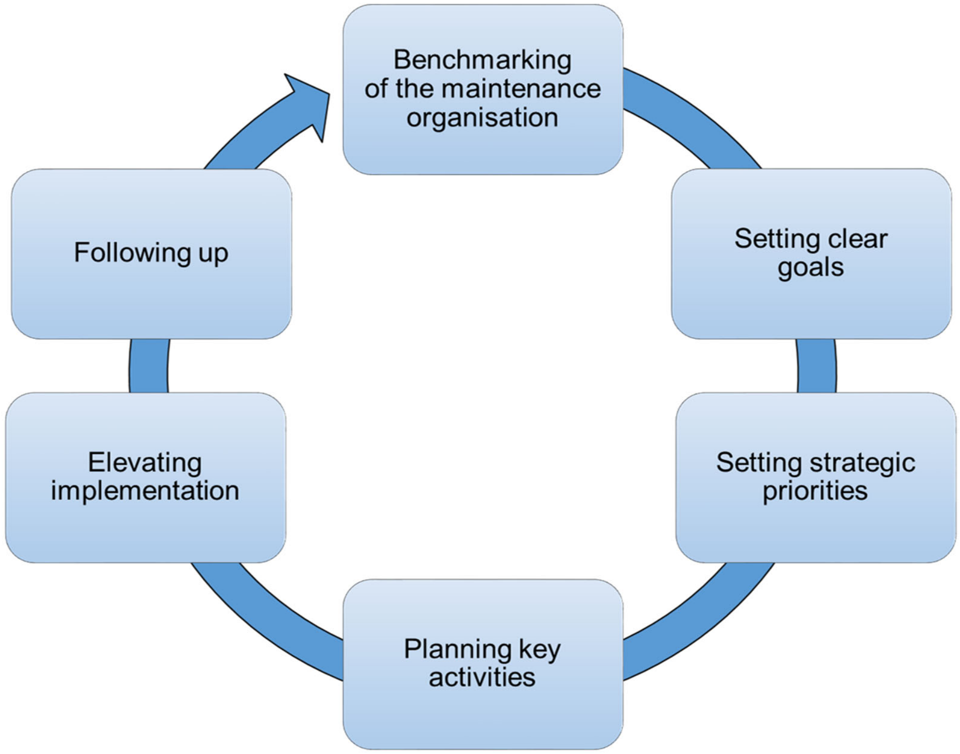


Figure 4: The proposed process, comprising six steps in strategy development for Smart Maintenance implementation. The figure is adapted from Appended Paper V.

1) A Smart Maintenance measurement instrument helps in assessing and benchmarking a maintenance organisation. It gives employees an understanding of the four dimensions of Smart Maintenance in their organisation. Visualisation of the results became a starting point for intense discussions and created *employee engagement*.

2) The goals of Smart Maintenance must link to the overall goals of the company. In other words, *strategic alignment*. *Internal communication* of the goals is essential to successfully engage other parts of the organisation (not just the maintenance function).

3) There is an *interplay among the four dimensions* of Smart Maintenance. It is important to ensure that the activities are executed in the correct sequence. Thus, it is important to set strategic priorities that helps in the *planning & scheduling of activities*.

4) Activities to improve the dimensions of Smart Maintenance must be identified and planned; preferably by bringing together the employees for a brainstorming workshop to create a dialogue and *employee engagement*. Visualising the activities in a roadmap helps in the *planning & scheduling of activities* and eases *internal communication*.

5) The next step is to elevate implementation by putting planned activities into action. However, various factors influence (by facilitating or inhibiting) the implementation of Smart Maintenance. For example, culture, leadership and IT security. Assessing a company in relation to such factors (using that company's strengths and being attentive to potential obstacles) could ease implementation.

6) Following up on activities and associated effects is necessary to link the effects of Smart Maintenance to the goals of the company in general and Smart Maintenance in particular. *Follow-up* on progress is necessary to maintain *employee engagement*. This makes it important to highlight accomplishments within all four dimensions of Smart Maintenance.

After some time working with the suggested activities, a new assessment using the Smart Maintenance measurement instrument allows potential new improvement areas for the maintenance organisation to be identified. Continuous development of a maintenance organisation ultimately benefits a company's development.

### Summary - strategic approach to Smart Maintenance implementation

A process is proposed to support a strategic approach to Smart Maintenance and its implementation (Appended Paper V). The proposed process comprises six steps: 1) benchmarking the maintenance organisation, 2) setting clear goals, 3) setting strategic priorities, 4) planning key activities, 5) elevating implementation and 6) following up. The process is cyclical; continuously assessing maintenance organisations and finding new improvement areas. It thus continuously develops maintenance organisations and their ways of working with Smart Maintenance.

# 5

# SMART MAINTENANCE IMPLEMENTATION - AN ORGANISATIONAL INNOVATION

*The results from the appended papers support the development of maintenance organisations towards meeting the demands of digitalised manufacturing. To position the thesis and make the results even more concrete and valuable to industry and academia, this chapter relates the results to the diffusion of innovations (DOI) theory (Section 2.1). It is a theoretical interpretation of the results, using innovation characteristics to describe how the organisation and all targeted employees can become increasingly skilful, consistent and committed to working with Smart Maintenance. Thus, it illustrates how industrial companies can succeed in their Smart Maintenance implementation.*

To understand organisational innovation in maintenance, we need to distinguish between *innovation adaption* and *innovation implementation* (Klein and Sorra, 1996). Smart Maintenance and its four dimensions are currently observable and measurable (please see Appended Paper V for an example of how the measurement may be used). This means that Smart Maintenance already exists to some extent in organisations (Smart Maintenance adoption). By contrast, implementation refers to "*[...] the transition period during which targeted organizational members ideally become increasingly skillful, consistent and committed in their use of an innovation*" (Klein and Sorra, 1996, pp. 1057). In other words, it makes the organisation and all targeted employees skilful, consistent and committed to working with Smart Maintenance. Conscious actions aimed at implementing Smart Maintenance necessitate a form of awareness. In practical terms, there are many different ways of working with Smart Maintenance and the specific implementation will differ between plants. However, to further describe how industrial companies may succeed in implementing Smart Maintenance in their plants, the research results presented in this thesis are related to the five innovation characteristics described in the DOI theory (Rogers, 2003): 1) relative advantage, 2) compatibility, 3) complexity, 4) trialability and 5) observability. Table 9 provides an overview of how the appended papers relate to these characteristics.

Table 9: Overview of how the appended papers relate to the characteristics described in the DOI theory.

| Characteristic | Paper I | Paper II | Paper III | Paper IV | Paper V | Paper VI |
|---|---|---|---|---|---|---|
| **Relative advantage** | x | | | x | x | x |
| **Compatibility** | | | | | x | x |
| **Complexity** | | x | | | x | |
| **Trialability** | | | | | x | |
| **Observability** | | | x | | x | x |

### Relative advantage

1) Relative advantage is the degree to which an innovation provides a perceived advantage (Rogers, 2003). It might entail financial aspects, social prestige and/or satisfaction leading to a higher degree of motivation for change. Calculating the ROI for organisational innovation tends to be tricky (Steiber, 2012). However, digitalisation in general and Smart Maintenance in particular do include investment to some extent. The categories of maintenance models from Appended Paper I can be used to understand and communicate relative advantages from different perspectives. For example, economic value, cost-effectiveness and function-orientated planning (please see Appended Paper I for details). In Appended Paper IV, four industry practitioners projected the advantages of using 5G technology in the manufacturing industry. Combining their estimates with a modified TOPSIS method, it became possible to link 5G and its key technologies to manufacturing performance (please see Appended Paper IV for details). The modified TOPSIS method has the potential to estimate the relative advantages of new technology. This study also determined that 5G technology will mostly impact productivity, flexibility and maintenance performance. It thus describes the relative general advantages of 5G. Above all, it is important to believe in relative advantage (Steiber, 2012). The maintenance leadership is described in Appended Paper VI, which highlights that the role of maintenance manager is currently transitioning from that of a technical manager to being a leader of organisational change within maintenance. It is this leader's responsibility to spread belief in the change; to create and communicate a vision that makes people want to follow the change. In Appended Paper V, the companies developed their Smart Maintenance strategy and used strategic alignment. They linked the advantages and goals of Smart Maintenance with their overall company goals. Further, the material developed by the companies during the study was used to communicate and justify why they should work with Smart Maintenance. In summary, the whole company must believe in the advantages of Smart Maintenance. To justify a change, the development towards Smart Maintenance might be advantageously packaged and communicated as in Appended Paper V. Support is available if quantitative arguments are important (examples in Appended Paper I and

IV). Above all, maintenance managers have a major role in communicating relative advantages of Smart Maintenance (Appended Paper VI).

### Compatibility

2) Compatibility is the degree to which the innovation fits the existing values and norms of an individual or organisation. The better the fit, the greater likelihood of innovation being implemented. Smart Maintenance is an organisational design and its four dimensions may be worked with in various different ways, to suit the organisation and the individuals working within it. In Appended Paper V, the companies started with the current state of their maintenance organisations (at the Smart Maintenance level). Doing so reduced the risk of them setting goals and ambitions that were too far ahead of their organisations, thus enhancing compatibility. The results of the benchmarking were discussed within each company, with employee engagement becoming clear in these discussions. Further, a workshop was held to brainstorm Smart Maintenance activities and supporting a mixture of bottom-up and top-down approaches (Boer and During, 2001). The employees had the opportunity to suggest activities, thus showing what they valued the most. Meanwhile, the maintenance organisation had to be linked to the overall business goals described in Appended Papers V and VI. The interviewees in Appended Paper VI also described how maintenance managers need to be able to set goals for individual employees. This is something that has become increasingly important in the face of digitalisation and is used to attract employees into the maintenance profession. It shows that Smart Maintenance also includes tasks attractive to ambitious people who value personal development. The interviewees also stated that the compatibility aspect should target young people and ensure future generations of maintenance employees. In summary, Smart Maintenance needs to fit the current values of an organisation. One of the companies (in Appended Paper V) linked its Smart Maintenance activities to its established values. This increased the compatibility as these values were familiar to the employees. Further, the work procedure described in Appended Paper V allows employees to discuss their current situation and jointly propose ideas on how to proceed in a way that benefits them. Moreover, Smart Maintenance needs to be linked to the overall business goals (Appended Papers V and VI) to ensure it fits with the whole company, clarifying the compatibility issue at a company level.

### Complexity

3) Complexity means that an innovation that is perceived as difficult to use or understand will be implemented to a lesser extent than one that is simple and easy to understand. Challenges to organisational innovations include the fact that, by nature, complexity depends on the individuals within an organisation and their perceptions (Greenhalgh et al., 2004). There are also difficulties of observation and interpretation (Steiber, 2012). Maintenance in digitalised manufacturing has been described by many different concepts, with varied terminology describing similar things. Smart Maintenance is a well-defined concept which aims to be easy to understand for both academics and industry practitioners. Working with a well-defined concept helps reduce complexity. Regarding necessary investment, Appended Paper II presents 11 factors influencing the investment process, which may make the investment process rather complex. Examples include fact-based decision-support, transparency and foresight.

Being aware of these and using them as an advantage can help people perceive the investment process as less complex. Please see Appended Paper II for more details. Further, Appended Paper V proposes a process for developing maintenance organisations, based on the Smart Maintenance concept and its associated measurement instrument. This measurement instrument provides industry practitioners with an understanding of Smart Maintenance within their organisation. The results from the measurement instrument can then be used to identify possible improvements in each of the dimensions of Smart Maintenance. The results can also be compared to an industry average. This generates intense discussion in which industry practitioners have the chance to reflect upon their organisations. Please see Appended Paper V for details of how the results from the measurement instrument were used. A clear and measurable concept (such as Smart Maintenance) put to structured use as in Appended Paper V makes it easier to understand the intended organisational innovation. It thus reduces complexity and increases the likelihood of successful implementation.

### Trialability

4) Trialability means that if it is possible to try an innovation in stages and learn by doing, the degree of uncertainty will decrease. Such an innovation will be more likely to be implemented compared to one that cannot be divided into several steps. Having a stepwise approach to innovation is particularly important to organisational innovation (Boer and During, 2001). Appended Paper V proposes a cyclical process of strategy development for implementing Smart Maintenance. This process suggests starting with the current state of a maintenance organisation and then phasing in new technology and new ways of working in stages. This creates a learning focus that benefits organisational innovation (Klein and Knight, 2005; Laforet, 2011); one in which the organisation and its individuals learn as the development takes place. By making changes in stages, the high degree of trialability may lead to a decrease in the perceived complexity of the organisational innovation. However, it is a prerequisite that such staged progress should be transparent (Boer and During, 2001) (as in Observability below). Stepwise implementation will decrease the level of uncertainty. If something unpredictable still crops up, then a mixture of top-down and bottom-up approaches will be beneficial. A top-down approach to set the direction and a bottom-up one so that employees can respond quickly to uncertainties (Boer and During, 2001). In summary, a stepwise implementation of Smart Maintenance, including a mixture of top-down and bottom-up approaches, increases the chances of success. The process described in Appended Paper V can ultimately be used to aid increased trialability.

### Observability

5) Observability relates to the degree of visibility of the innovation's results. If the results are easy for individuals to see, an innovation is more likely to be implemented compared to one with less prominent results. Internal diffusion (meaning communication and visualisation of the progress and results of the innovation) is critical to organisational innovation (Boer and During, 2001; Klein and Sorra, 1996). In Appended Paper V, the companies in the study emphasised the importance of following up the planned activities and any effects. Performance indicators (PIs) can be used to help check operations by following up a set of measurements. These are then compared to a set target and take action accordingly. In Appended Paper III, 170 maintenance PIs were

analysed, based on the anticipated effects of Smart Maintenance. Although a wider range of effects is anticipated from Smart Maintenance than from traditional maintenance (please see Appended Paper III for details), there is no need to develop new PIs for this purpose. Rather, there is a need to increase integration in the use of PIs. For example, Smart Maintenance is expected to lead to employee satisfaction. However, the main responsibility for following up on related PIs may not lie with the maintenance organisation. Rather, the maintenance organisation should have a dialogue with human resources (an HR department). The effects of Smart Maintenance are on a wider palette than maintenance performance. The results of Smart Maintenance might be captured in another department. Thus, it is important to integrate the use of PIs so as to increase observability. Further, the role of maintenance managers will include follow-up, not only on PIs but also on employees and their individual goals. In Appended Paper VI, the maintenance manager is described as a leader, responsible for ensuring that individual employees can develop personally and contribute to the results of the organisation. In summary, Appended Paper V shows the importance of being transparent about the progress of implementing Smart Maintenance; continuously checking what has been done and whether it has in any way yielded results. The categorisation of the 170 PIs in Appended Paper III can help in identifying relevant PIs to follow-up, but the most important lesson is that the results of Smart Maintenance must be followed up across functions to ensure full observability.

### Making Smart Maintenance implementation an organisational innovation

All five innovation characteristics are important in explaining the rate at which innovations are spread. The more characteristics that can be considered, the more likely it is that a Smart Maintenance implementation will succeed. For industry practitioners, this means they need to understand these five characteristics within their organisations, particularly in the context of maintenance. The nature of organisational innovation makes it important to truly believe in the advantages of Smart Maintenance. Further, Smart Maintenance and its implementation need to fit with the existing values and norms of an organisation, bearing in mind the value-fit between Smart Maintenance and all targeted employees to ensure a high degree of compatibility. Implementing in stages and allowing learning by doing reduces complexity and ensures trialability. Observability can be ensured by visualising the progress of the implementation and its results. From a research perspective, the DOI theory has the potential to structure the research being conducted; it clarifies what needs to be studied (the five characteristics). Linking the research to these five characteristics makes it easier to understand how research is interrelated and how it can help advance research into maintenance in digitalised manufacturing.

# 6 DISCUSSION

*This chapter provides a discussion of the research presented in this thesis. It starts with an overall discussion, to provide further answers to the research questions. There then follows a discussion of academic and practical contributions and a methodological discussion. The chapter ends by proposing future research.*

## 6.1 FACILITATING THE IMPLEMENTATION OF SMART MAINTENANCE

While technology is the main research interest within the maintenance field (Roy et al., 2016; Silvestri et al., 2020), this thesis contributes with aspects that are less researched, such as strategy, leadership and organisational structures (Balakrishnan and Das, 2020; Bokrantz et al., 2020b; Gürdür et al., 2019). Further, the DOI theory (Rogers, 2003) was used to interpret the research results and further understand how they may be used to support the implementation of Smart Maintenance. In other words, supporting the intended organisational innovation in maintenance. Using established theories to explain findings rarely happens in maintenance research and could probably be more widely used in the research field. Hopefully, using a theory from another research field will make the results of this thesis easier to assimilate and indeed put into practice. The DOI theory has been used in a variety of disciplines (Dooley, 1999; Makse and Volden, 2011), with a specific aim in operations management to bring academic research closer to real-world practice (Waring and Alexander, 2015). Albeit rarely, DOI has also been used in maintenance research. A recent study used DOI to study the integration of Industry 4.0 technologies and TPM practices (Tortorella et al., 2021). An innovation perspective of maintenance in digitalised manufacturing is on the rise. Ideally, this thesis is pioneering this perspective and accelerates the innovation in maintenance. Leastways, the author has learned a great deal from this process.

A paradox of maintenance is that its effects are usually deferred, making it a challenge to visualise benefits up-front and justify investment. Many attempts have been made in research to quantify the positive effects of maintenance, as well as the effects of a lack of maintenance, for example, Al-Najjar and Alsyouf (2003) and Salonen and Deleryd (2011). Fact-based decision-support was one of the influencing factors identified in Appended Paper II. Models like those in Appended Paper I can be used to support the preparation of investment proposals. Still, what matters is having belief in the ***relative advantage*** (Steiber, 2012) of Smart Maintenance. This thesis shows that several factors influence the investment process (Appended Paper II), not just financial calculations.

When it comes to Smart Maintenance management, much research has focused on technology to support the new way of working (Kłos and Patalas-Maliszewska, 2018;

Bodo et al., 2020; Ashjaei and Bengtsson, 2017; Blaszczyk and Wisniewski, 2019). Further, the advancement of maintenance management is commonly assessed using many criteria relating to technology use (Kans 2010; Macchi et al., 2017; Mehairjan et al., 2016; Nemeth et al., 2019; Oliviera and Lopes 2020). To advance Smart Maintenance management and support organisational change, there is a need for leadership (Battilana et al., 2010; Stouten et al., 2018). This is a rarely explored area in the maintenance context. This thesis (Appended Paper VI) provides empirical insights into the changing aspects of leadership in maintenance; it deals with organisational change, including individuals who should find their role and purpose in the new organisational setting. Ensuring ***compatibility*** (that the new way of working fits the individuals' current values of the) becomes important (Klein and Sorra, 1996; Steiber, 2012) and is the maintenance manager's responsibility (Appended Paper VI). Thus, a change is made, from maintenance management to maintenance leadership.

Besides the responsibility for leading an organisation as it changes, there is also a need to manage daily operations. Performance indicators are one way of doing this and involves certain measurements being compared to targets or expectations, with actions directed accordingly (Neely et al., 1995; Rouse and Putterill, 2003). Several maintenance PIs are available with the most commonly used in industry relating to the internal efficiency of maintenance (Bokrantz et al., 2020b; Bengtsson and Salonen, 2011). This includes such things as mean time for repairs (Parida and Kumar, 2006). The EN 15341 maintenance standard (CEN, 2007) includes 70 maintenance PIs divided into three categories. A more extensive categorisation of PIs is suggested by Parida and Chattopadhyay (2007); this has seven categories. Such categorisation can support the selection of PIs that capture both the internal efficiency and external effectiveness of maintenance (what is done within the maintenance organisation and how it affects the production system) (Bokrantz et al., 2020b; Bengtsson and Salonen, 2016). It is anticipated that Smart Maintenance will lead to a wide range of effects. Appended Paper III includes a palette of PIs, divided into 13 categories to support the selection of PIs for following up Smart Maintenance initiatives. However, there may still be challenging to follow up on the implementation of Smart Maintenance. For example, cause-effect relationships are not always clear, albeit important (Rodriguez et al., 2009; Kang et al., 2016b). Effects of implementation primarily in the maintenance function may have effects on other parts of the system (Ingemarsdotter et al., 2021). Thus, the effects of Smart Maintenance may not be captured by only using PIs related to the internal efficiency of maintenance. Ideally, the use of PIs should be integrated across functions to capture the full range of results from working with Smart Maintenance. This may increase the ***observability*** of Smart Maintenance, which is an important aspect of organisational innovation (Boer and During, 2001; Klein and Sorra, 1996).

Within maintenance, there is a need for holistic strategies in general (Bengtsson and Salonen, 2009) and Smart Maintenance in particular (Bokrantz et al., 2020c). Some research has viewed a maintenance strategy as a choice between corrective (CM), preventative (PM) and condition-based maintenance (CBM) (Al-Najjar and Alsyouf, 2003; Bevilacqua and Braglia, 2000; Gutschi et al., 2019; Shyjith et al., 2008; Tan et al., 2011; Wang et al., 2007). Indeed, it is important to carry out effective maintenance by efficiently doing the right task at the right time. However, holistic strategies also include culture and organisational structure (Bengtsson and Salonen, 2009; Tsang 2002), knowledge and skill development (Tsang, 1998) and organisational priorities to serve as guidance in unpredictable situations (Mintzberg et al., 1999). Inspired by Salonen (2011), Jarzabkowski et al. (2007) and Mintzberg and Waters (1985), this thesis has adopted more of a holistic approach to maintenance strategies. Further, the strategy development process proposed in Appended Paper V is strongly related to all five characteristics in the DOI theory: **relative advantage, compatibility, complexity, trialability and observability**. Thus, Paper V will offer an important contribution to implementing Smart Maintenance.

## 6.2 ANSWERING THE RESEARCH QUESTIONS

Six studies were conducted to answer the three research questions (RQ1-3) in this thesis, with the aim of facilitating the implementation of Smart Maintenance. The three research questions are best explained in sequence and are thus answered in order:

### RQ1: How can Smart Maintenance investments be justified?

There are several models and methods available to quantify and describe the effects of maintenance and new technology, such as those in Al-Najjar and Alsyouf (2003), Salonen and Deleryd (2011) and Wu et al. (2015). Models from Appended Paper I and the modified TOPSIS method described in Appended Paper IV can be used to help justify Smart Maintenance investment. However, quantifying the effects of maintenance is not the only important thing when justifying investment. Various factors influence the investment process (Appended Paper II), such as fact-based decision-support, internal integration and foresight. Awareness of these can benefit the preparation of investment proposals and ease the decision process.

### RQ2: How can Smart Maintenance initiatives be managed?

Managing Smart Maintenance initiatives is about dealing with people in change and following up a wide range of effects. Many maintenance PIs can be used to manage Smart Maintenance initiatives (Appended Paper III) and by running follow-up activities as to their effect and then acting accordingly. To cover the full range of anticipated effects from Smart Maintenance, the use of PIs needs to be integrated across functions. Further, the role of maintenance manager is that of dealing with people in change, rather than being a traditional technical manager (Appended Paper VI). An overall consideration model describes how maintenance managers need to approach the changing maintenance organisation with particular emphasis on people, processes and technology. Specifically, these relate to the change itself and resistance to it, roles and responsibilities within maintenance, competence, goals, coherence within the organisation, dependencies outside the organisation and social practices.

### RQ3: How can a strategic approach to Smart Maintenance implementation be developed?

This thesis proposes a strategic approach to the implementation of Smart Maintenance, comprising six steps: 1) benchmarking of the maintenance organisation, 2) setting clear goals, 3) setting strategic priorities, 4) planning key activities, 5) elevating implementation and 6) following up (Appended Paper V). The process is cyclical, continuously assessing the maintenance organisation and finding new improvement areas. This is done to develop an organisation and its way of working with Smart Maintenance.

## 6.3 ACADEMIC AND INDUSTRIAL CONTRIBUTION

The research presented in this thesis was conducted in an applied manner. As a researcher, it has been a great opportunity; conduct research meanwhile contributing to solving real-life industrial problems. The research was funded by the Swedish innovation agency, whose intention is to use the research to make an industrial impact. Still, the academic contribution may not be underestimated. Through its six studies, this thesis has made important contributions to both academia and industry.

### Academic contribution

Within maintenance research, the emphasis has long been on technology. However, since the realisation that digitalisation is not just about technology, maintenance as a research field has begun to garner more organisational attention. This thesis is a contribution to the collected knowledge on the subject. Insights from RQ1, about investment (Studies A, B and D), summarise the research field and examine different ways of quantifying or describing the effects of maintenance. However, they also widen the research field as various factors influence the investment process. The answers to RQ2, about managing Smart Maintenance (Studies C and F), have contributed insights into *what* to measure and follow up (PIs, Study C) and *how* to follow it up (leadership aspects, Study F). Above all, Study F makes a major contribution to the maintenance research field, with its unique insights into leadership in maintenance. Study F is entirely based on practitioners' experiences and projections. Insights from RQ3, about a strategic approach to Smart Maintenance implementation (Study D), have contributed to holistic maintenance strategies; these have been on the research agenda before. Based on such maintenance strategies, plus insights from general strategy development, a new way of developing strategies has been proposed, specifically aimed at Smart Maintenance.

It is unusual to consider the implementation of maintenance in digitalised manufacturing as an organisational innovation. The results (from Studies A-F) were interpreted using the DOI theory (Rogers, 2003); a way of structuring research findings through a common language for researchers. It has the potential to support an understanding of how research results relate to each other. Further, it shows how these can jointly advance the research field of maintenance in digitalised manufacturing.

### Industrial contribution

The findings of this thesis can be used as a framework, providing industry practitioners with evidence-based guidance in their Smart Maintenance implementation. Practical implementation of Smart Maintenance will differ between plants but it will help if they can follow principles that aid implementation. The insights from all the Studies (A-F) were structured using the DOI theory. This aids understanding of what industry practitioners can do within their organisations to make their Smart Maintenance implementation a success. Above all, the strategy development process proposed in Appended Paper V provides step-by-step guidance on strategically approaching the implementation of Smart Maintenance. This process can be used directly by maintenance managers and will help them weigh up relative advantages, compatibility, complexity, trialability and observability. Referring to these five characteristics will increase the likelihood of successful Smart Maintenance implementation, assist in continued development towards digitalisation and thus help an organisation move towards increasingly competitive and sustainable production systems.

## 6.4 METHODOLOGICAL DISCUSSION

Following sections provide a brief discussion of each of the studies and their methods.

### Quality of research: rigour and relevance

To impact both academia and industry, I strove to produce rigorous research of practical relevance (Schultz, 2010; Vermeulen, 2005). In terms of practical relevance, the questions asked must be ones of importance to industry practitioners (Vermeulen, 2005). The practical relevance of this thesis has been achieved by asking research questions relevant to industry practitioners and by conducting four of the studies in an industrial setting (Studies B, D, E and F). The three research questions in this thesis reflect the research process and, largely, how industry practitioners think. The world is in the middle of a technological shift and there is a need for investment in technology (RQ1). However, if the full effect of technology is to be realised, that technology and those using it must be managed and its effects must be followed up (RQ2). This needs to be packaged as a strategic approach, if it is to produce structured work with Smart Maintenance implementation (RQ3). These are relevant research questions as there is a need for research focusing on the development of the maintenance organisation to complement the technology-focused research (Silvestri et al., 2020).

In terms of rigour, the right type of method needs to be selected and carefully executed (Vermeulen, 2005). No single method helps understand either the complex real world, or the implementation of Smart Maintenance. This thesis has used a mixed-methods approach (Creswell, 2013) to study the implementation of Smart Maintenance from several perspectives and has selected a method appropriate to the aims of each study. The methodology of each study is discussed below.

The findings of this thesis can certainly be applied to the type of companies that participated in this research. The cases and participants in the empirical studies were selected strategically based on their interest in developing their maintenance organisation. Many of them are at the forefront, with dedicated resources for starting to implement Smart Maintenance. However, using an established theory, such as DOI (Rogers, 2003) has been a way to interpret the results rigorously and gain the positive effects of generalisability. This makes the results relevant and applicable to more companies. Innovation also has the potential to reduce resistance to change and instead convey positive associations through the implementation of Smart Maintenance.

### Methodological discussion of each of the studies

A more extensive methodological discussion of each of the studies (Studies A-F) is provided in each of the appended papers (Appended Papers I-VI). A brief discussion of the studies and methods are provided in the following sections.

Many maintenance models have been developed in research to quantify or describe the effects of maintenance. Study A brings clarity by using suitable models for different purposes. A structured overview of maintenance models was provided through a literature study followed by an inductive categorisation of the models. This categorisation was done by a team of three researchers following a procedure inspired by constant comparison (Glaser and Strauss, 1967) to ensure rigorous categorisation.

Studies B and E were case studies, aiming for in-depth examination of maintenance-related investments and maintenance strategy development. The results of both cases rely on data collected using multiple methods, for triangulation purposes (Denscombe, 2014; Yin, 2018). Further, it was clearly shown how data was interpreted into findings from which conclusions were drawn (Ketokivi and Choi, 2014). Thus, transparency, an important but often neglected aspect of case study research (Barratt et al., 2011), was deemed to have increased the trustworthiness of the results. The cases were sampled to gain an in-depth understanding of the phenomenon being studied. Also, the cases were strategically sampled from different industrial sectors, with the aim of gaining the positive effects of generalisability by learning from different industrial sectors.

Study C categorised maintenance PIs for Smart Maintenance. One hundred and seventy (170) maintenance PIs were collected from publications and further analysed in a rigorous procedure based on intercoder reliability and negotiated agreement (Campbell et al., 2013) to ensure the credibility of the results. The coding was done twice by two equally knowledgeable researchers, with negotiation between the two codings and after the last one. This procedure resulted in a rigorous categorisation of PIs for Smart Maintenance.

Study D used quantitative and qualitative methods to determine the impact of 5G technology in the manufacturing industry. Four respondents might not be sufficient for full generalisability of 5G technology in manufacturing. However, all respondents are knowledgeable in manufacturing, 5G technology and the demos in the study. This provided high-quality input to the study. Quantitative data was collected and analysed to gain a broad understanding of the impact of 5G technology on manufacturing performance. The analysis was based on a modified TOPSIS method (Hwang and Yoon, 1981) to ensure the robustness of the results. Qualitative data was collected and analysed to gain an in-depth understanding of the value of 5G technology. The modified TOPSIS method enables analysis of the relationship between technology characteristics and manufacturing performance. The combination of using domain experts in the manufacturing industry and a structured mathematical evaluation helps identify opportunities and challenges for implementing digital technologies (McAfee and Brynjolfsson, 2012).

In Study F, 20 semi-structured interviews were conducted to explore how leadership in maintenance is changing in the face of pervasive digitalisation. The empirics of the topic were relevant and of high quality. All interviewees were recruited through membership in a Swedish professional interest organisation focusing on sustainable maintenance management. This provided insights from people who are both interested and experienced in developing maintenance organisations. This strengthens the study's position on leadership in maintenance. Further, two open-ended questions were asked.

These allowed the interviewees to freely associate regarding leadership in maintenance, with minimum influence from the interviewer (thus reducing researcher bias). The analysis was based on a socio-technical systems (STS) framework (Davis et al., 2014); aimed at a rigorous analysis of the interviews, rather than a purely descriptive analysis. The interviewee sampling, data collection and data analysis were reported in detail using consolidated criteria for reporting qualitative research (COREQ) (Tong et al., 2007), with the aim of having a positive effect on the credibility of the results.

## 6.5 LIMITATIONS

This thesis assumes the theoretical domain of Smart Maintenance implementation to include all organisations with a maintenance function. Instead of limiting the theoretical domain of this thesis solely to the manufacturing industry, empirical data was collected from a variety of industries across multiple industrial sectors. This was done in the spirit of external integration of Smart Maintenance, to learn from other sectors. However, most of the empirical data was collected from organisations within continuous and discrete-part manufacturing, thus making the manufacturing industry the main application area for the findings of this thesis. More empirics from other industrial sectors are needed to say with certainty that the findings of this thesis are applicable to all organisations with a maintenance function.

This thesis developed support for Smart Maintenance implementation but did not include testing of the results (applying the framework in this thesis). The companies involved in the research projects have tested certain parts of the research results to support their Smart Maintenance implementation. However, the way is open for future research to apply the full framework presented in this thesis.

## 6.6 FUTURE WORK

Future work is suggested which tests the framework within which Smart Maintenance meets organisational innovation, to support the implementation of Smart Maintenance in the manufacturing industry. However, organisational innovation in maintenance is not limited to the manufacturing industry. Might the findings in this thesis be applied in more industries which have facilities or equipment to maintain, or to all organisations with a maintenance function? Does the DOI perspective make it easier to apply the findings in other domains? More research is needed to test the specific domains in which the results of this thesis can be used.

This thesis used the five innovation characteristics (explained by the DOI theory) to describe how its results can support the implementation of Smart Maintenance. The next step is to conduct further targeted efforts. Which characteristics have the strongest impact? Does the effect of different characteristics differ between different industries, company size, plant size, organisational structures, culture and so on? Are any of the characteristics more difficult to handle and what are the consequences? If we could gain an in-depth understanding of the innovation characteristics in the maintenance context, it will be possible to be even more precise about how industrial companies can succeed with their Smart Maintenance implementation.

# 7 CONCLUSIONS

This thesis provides support for organisational innovation in maintenance in which the organisation and all targeted employees become increasingly skilful, consistent and committed to working with Smart Maintenance. It enables the implementation of Smart Maintenance to meet the demands of digitalised manufacturing.

Seeing Smart Maintenance from an organisational innovation perspective facilitates its implementation by considering five innovation characteristics: relative advantage, compatibility, complexity, trialability and observability. Investment in Smart Maintenance cannot rely solely on financial calculations. There is a need for true belief in the *relative advantage* of maintenance. *Compatibility* can be ensured by adopting Smart Maintenance initiatives that fit the current state of the maintenance organisation, including its existing values and norms. Change should be made in stages to reduce its *complexity* and increase *trialability,* using a mixture of top-down and bottom-up approaches. *Observability* should be ensured by communicating and visualising the progress and the results of the change. The use of performance indicators should be integrated to capture the full range of Smart Maintenance effects. The maintenance manager's task and responsibility are to manage people in change. A strategy development process for Smart Maintenance implementation is proposed, to support organisational innovation in maintenance. The process is cyclical and has six steps:

1. Benchmarking of the maintenance organisation.
2. Setting clear goals.
3. Setting strategic priorities.
4. Planning key activities.
5. Elevating implementation.
6. Following up.

This step-by-step process can be applied directly by maintenance managers. Combined with the insights of this thesis, it can serve as a framework to guide industry practitioners in their Smart Maintenance implementation. In research terms, implementing maintenance in digitalised manufacturing is seldom deemed organisational innovation. This perspective potentially advances the research field, through more targeted efforts to facilitate the implementation of Smart Maintenance.

Organisational innovation in maintenance is needed to meet the demand for digitalised manufacturing. Supported by this thesis, industrial companies can continue their development towards digitalisation and thus move towards increasingly competitive and sustainable production systems.

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